Physics of Neutrino Detection

Roxanne Guenette
Harvard University

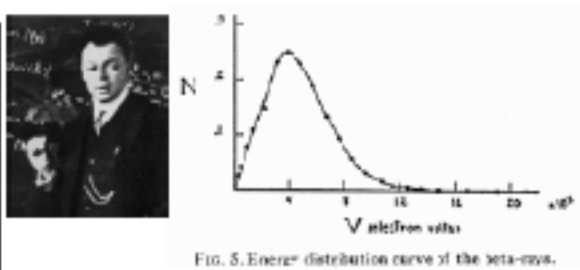
23 August 2017

Outline of the Lecture

Neutrino detection has been highly focused on single purpose for a long time. It is only relatively recently that broader efforts are dedicated to neutrino detection, and this is mainly led by the large size of detector required and the limited funding…

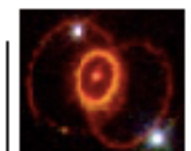
- Brief historical review of neutrino detection
- The scientific context (challenges) of neutrino detection
- Detection techniques and neutrino detector overview
- Future of neutrino detection

Neutrinos - The First 85 Years of Discoveries



1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory



1987 SN 1987A

1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar ν_e flavor change.

2015

2003 KamLAND discovers disappearance of reactor $\overline{\nu}_e$

?

1968 Ray Davis detects solar neutrinos.

2002

1962 Steinberger, Lederman, Schwartz, et al demonstrate ν_e & ν_μ

1988

1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate

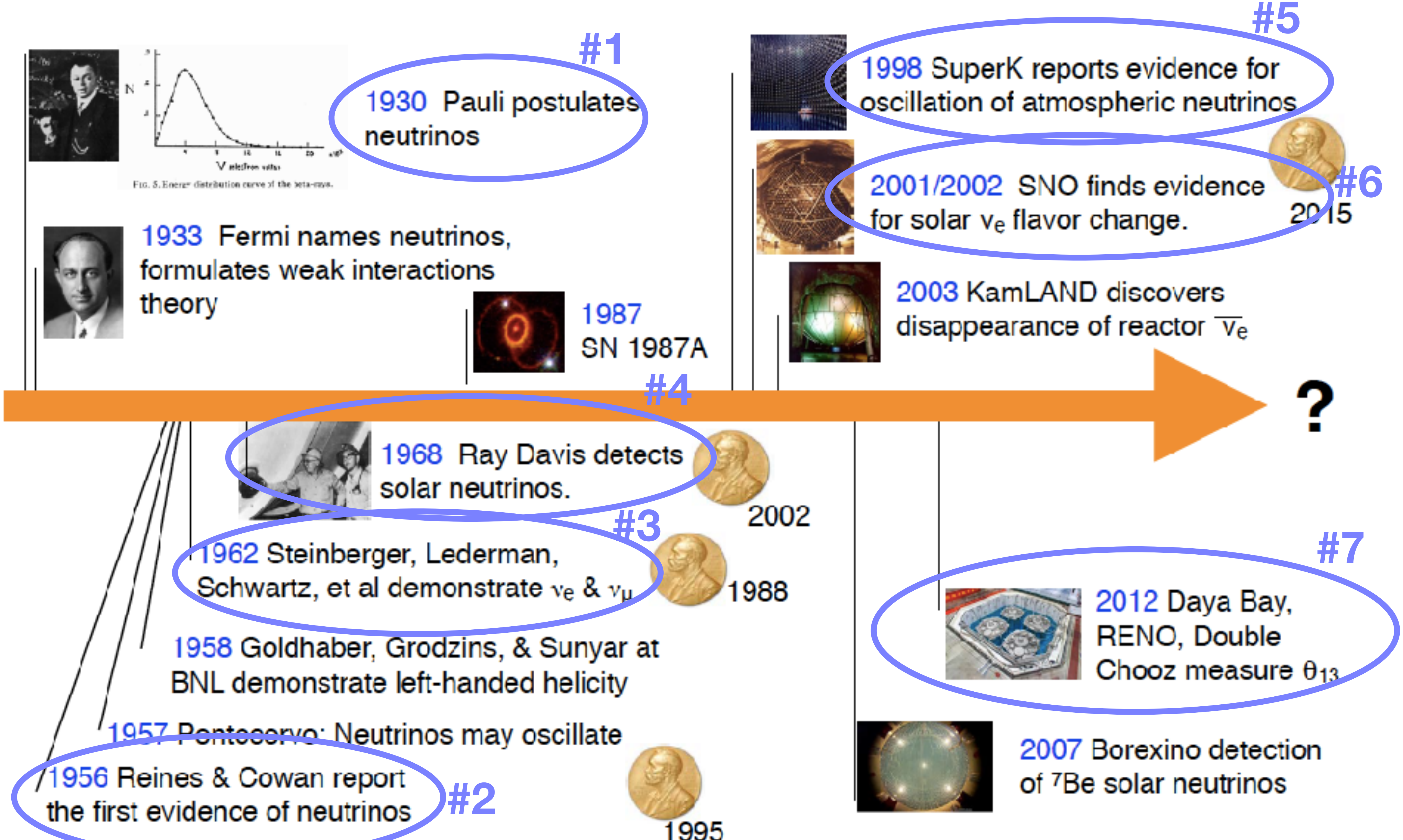
1956 Reines & Cowan report the first evidence of neutrinos

1995

2012 Daya Bay, RENO, Double Chooz measure θ_{13}

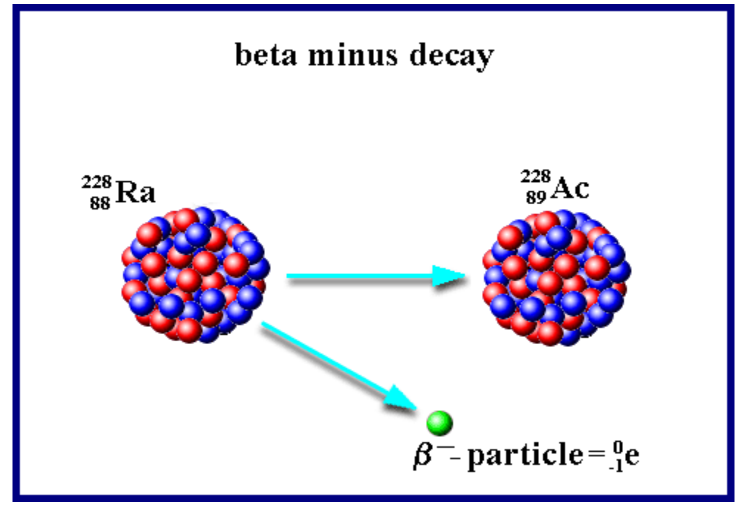
2007 Borexino detection of ^{7}Be solar neutrinos

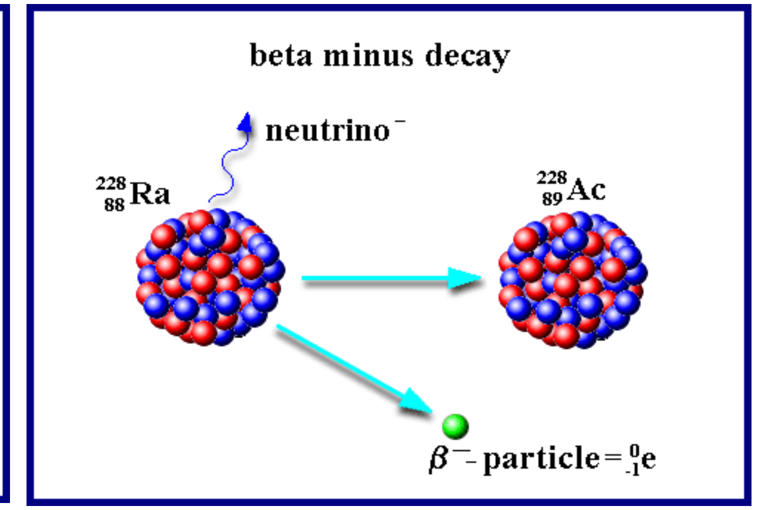
Neutrinos - The First 85 Years of Discoveries

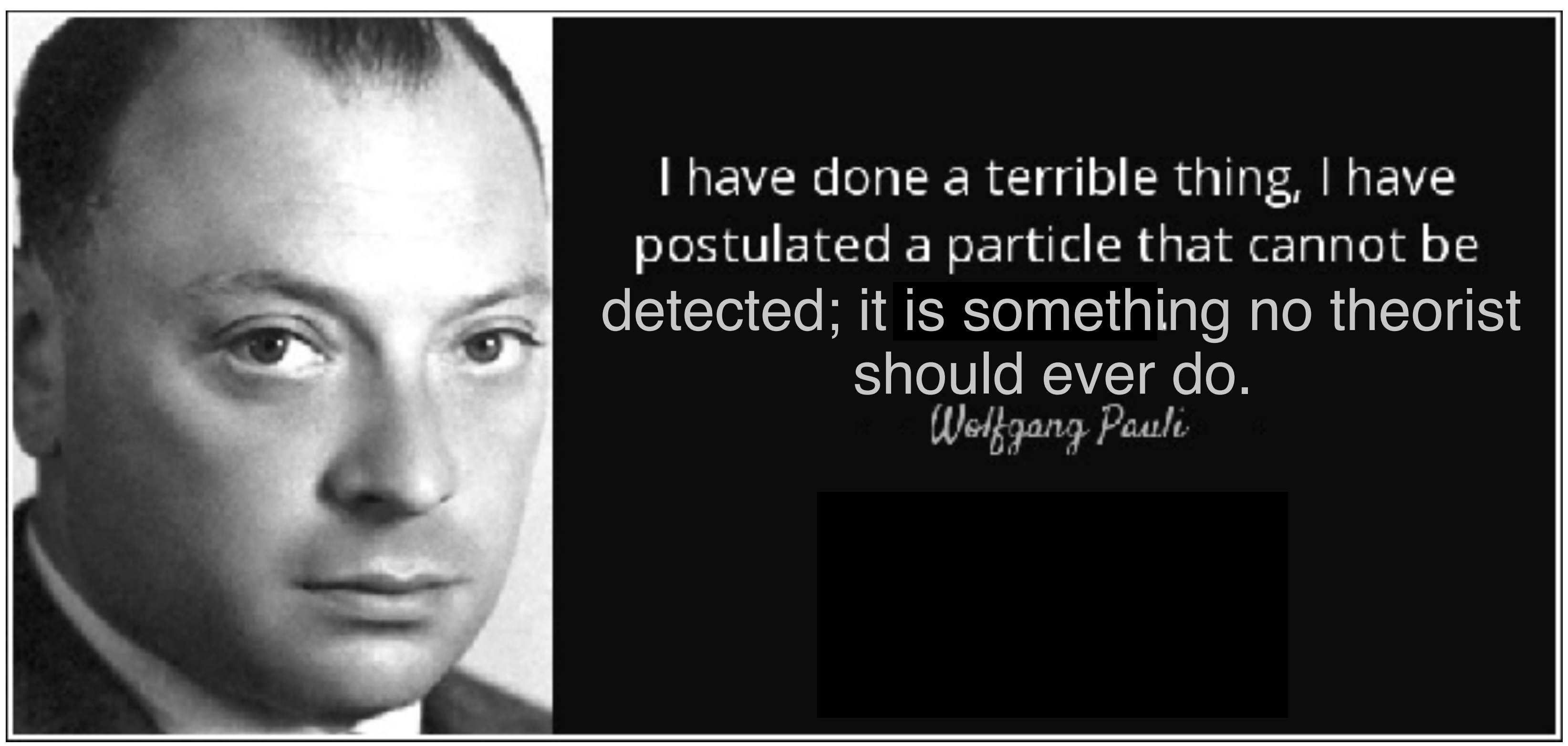


A brief history of the 3 neutrinos

- Postulated by W. Pauli in 1930

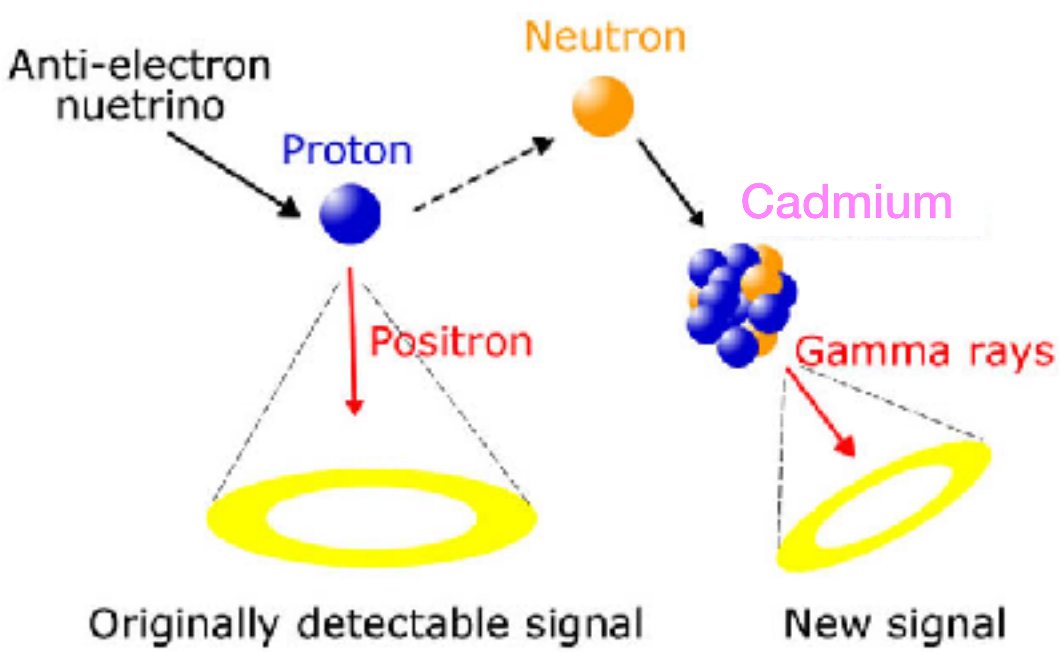


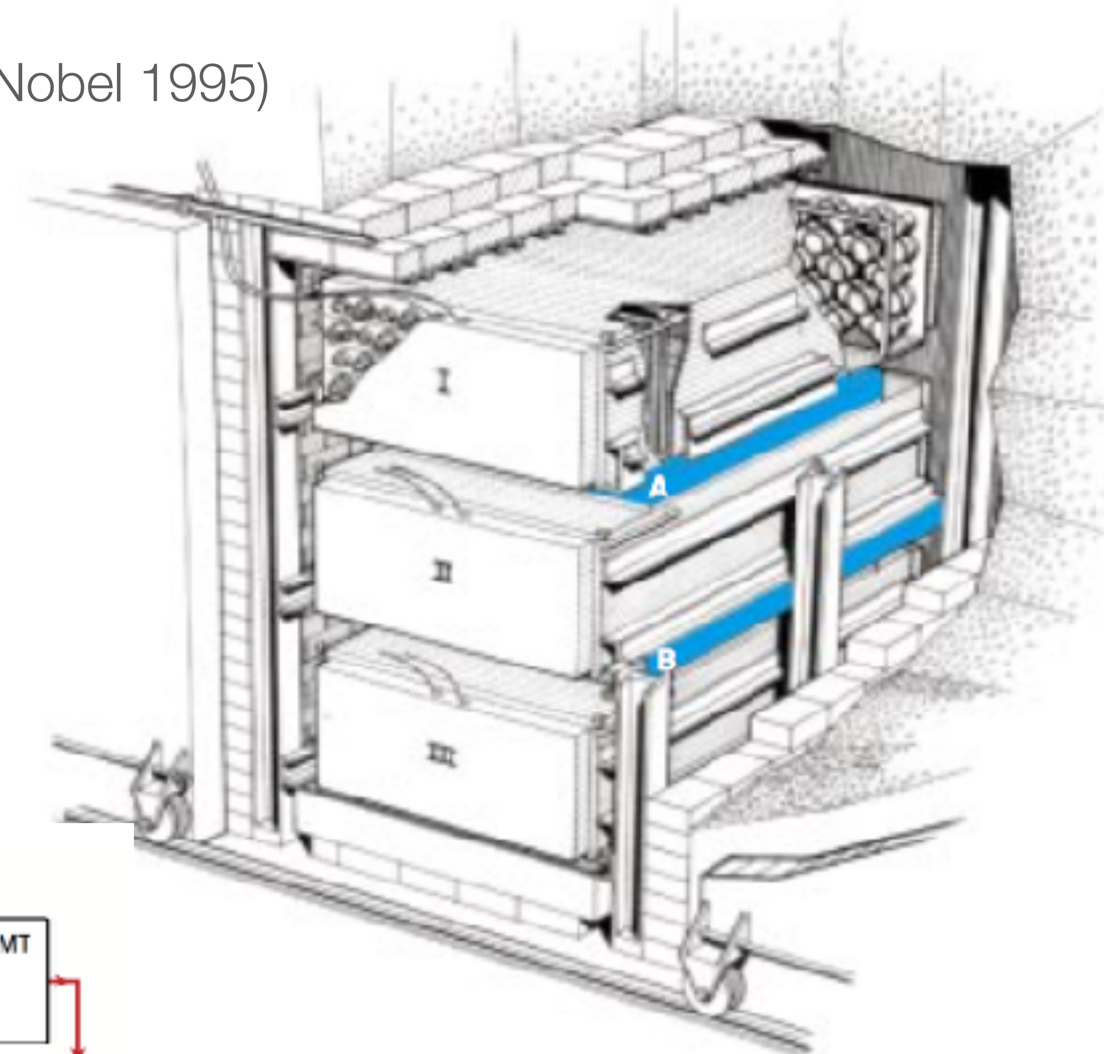


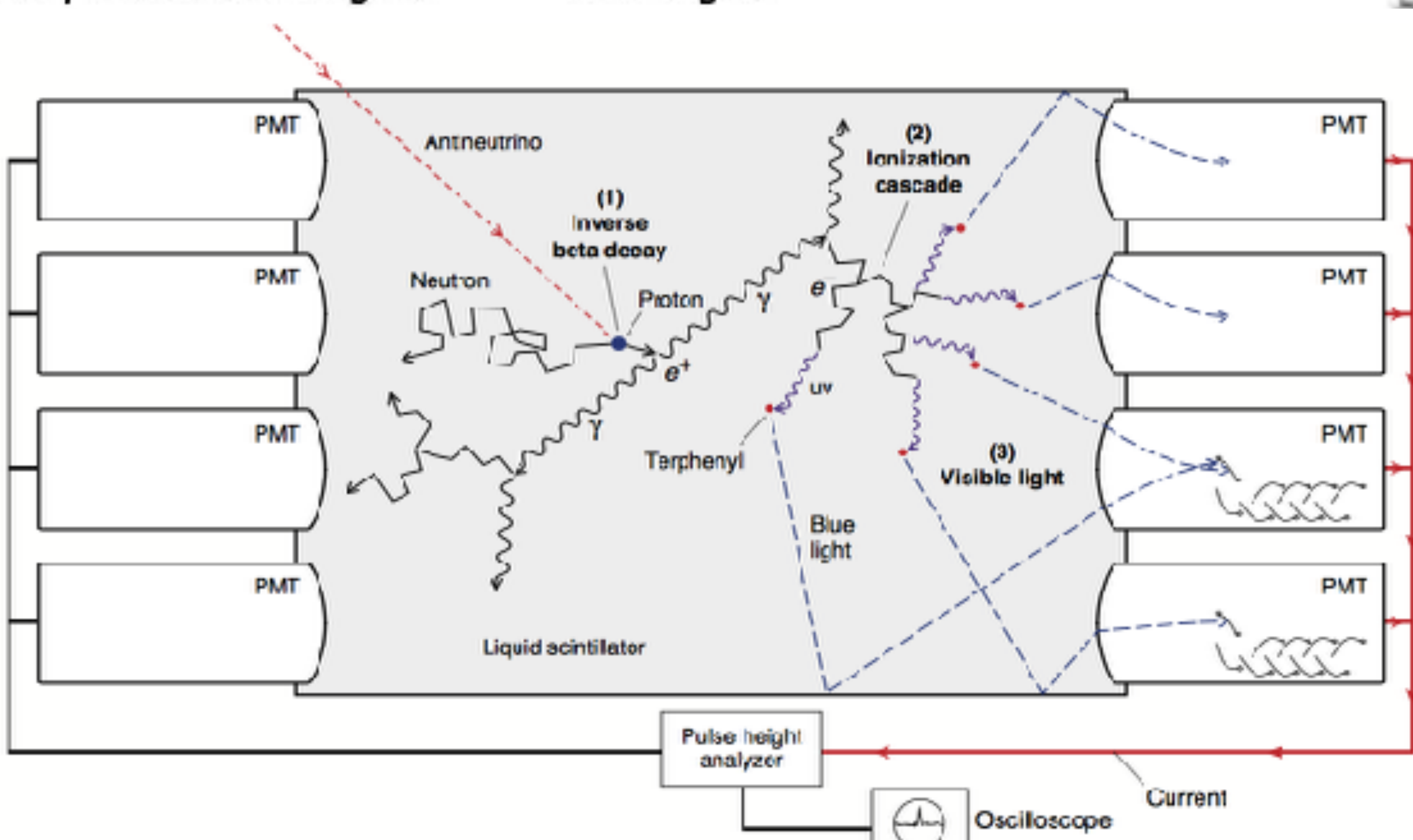


A brief history of the 3 neutrinos

- Detected ($\overline{\nu}_e$) in 1956 by Reines & Cowan (Nobel 1995)

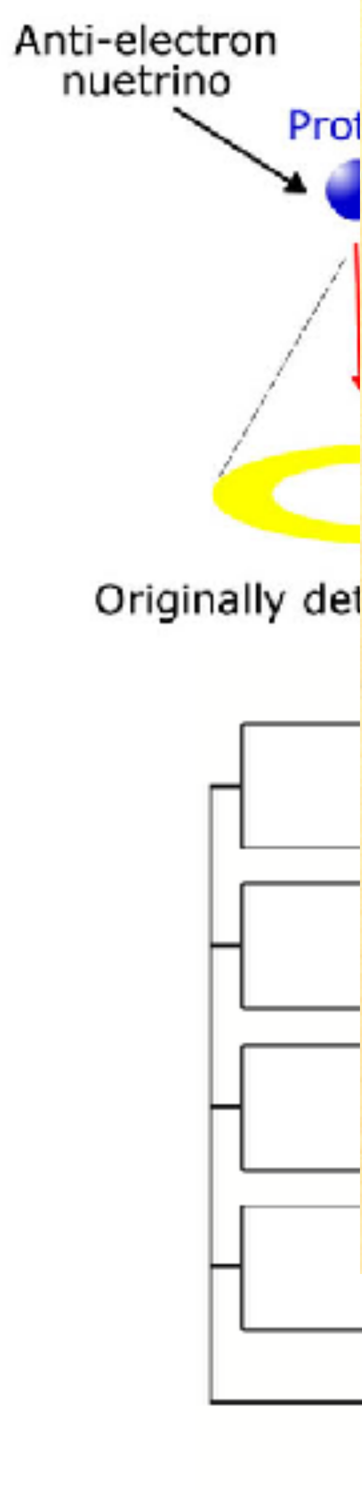


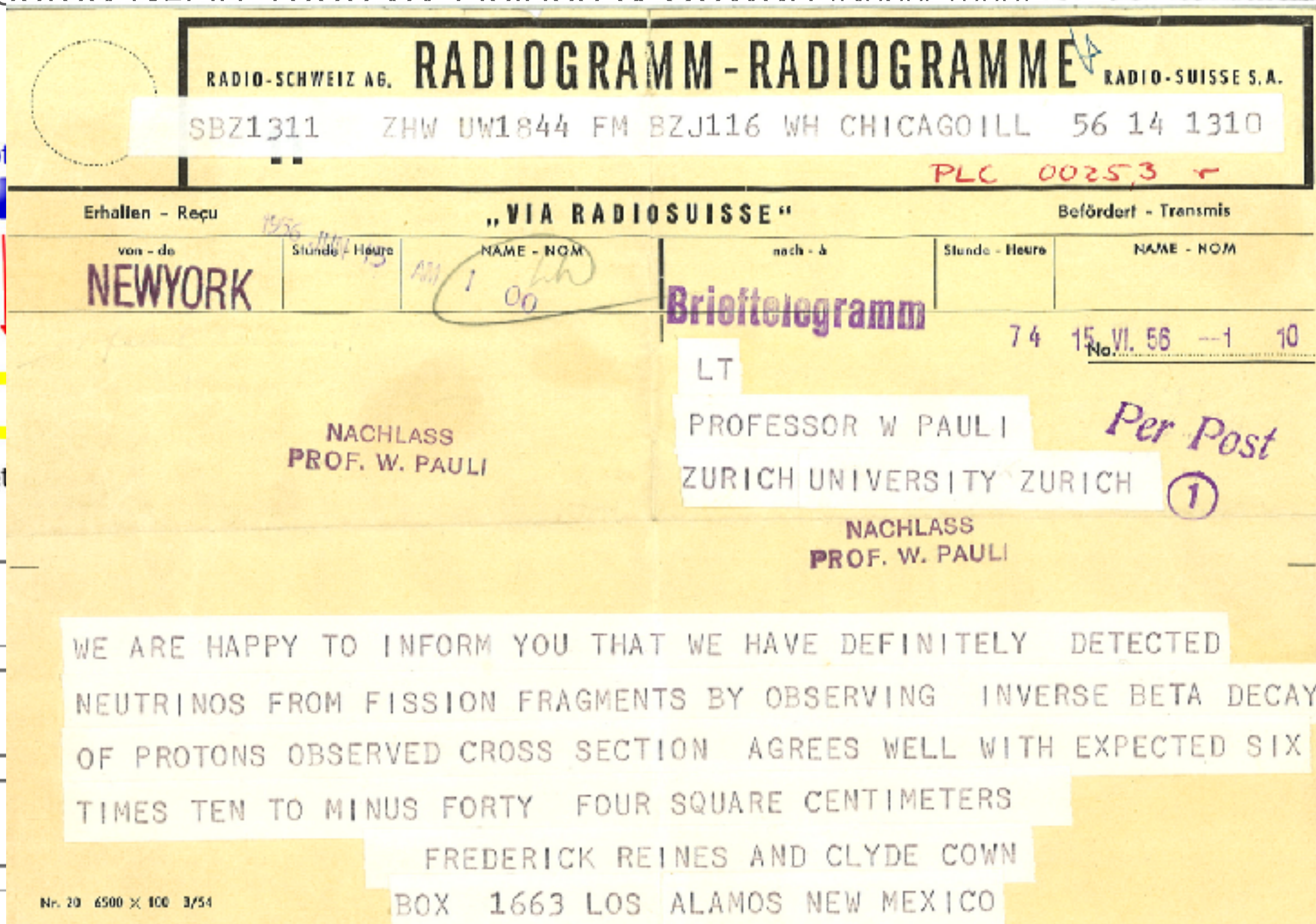




A brief history of the 3 neutrinos

- Detected ($\overline{\nu_e}$) in 1956 by Reines & Cowan (Nobel 1995)





RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK			Brieftelegramm		

74 15.VI.56 --1 10

No.

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

1

NACHLASS
PROF. W. PAULI

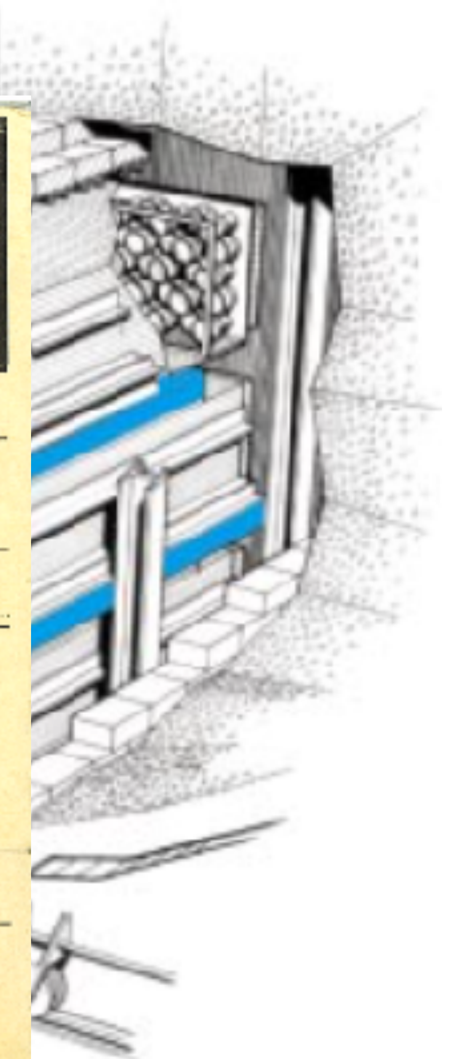
NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

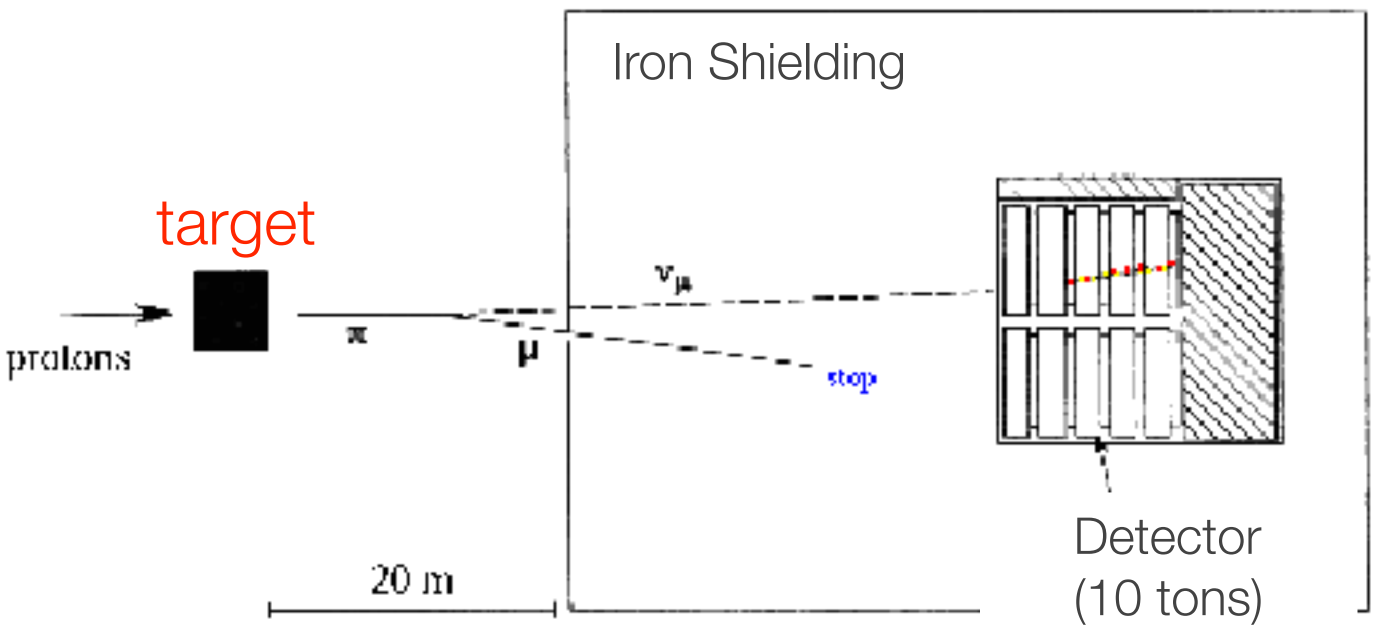
BOX 1663 LOS ALAMOS NEW MEXICO

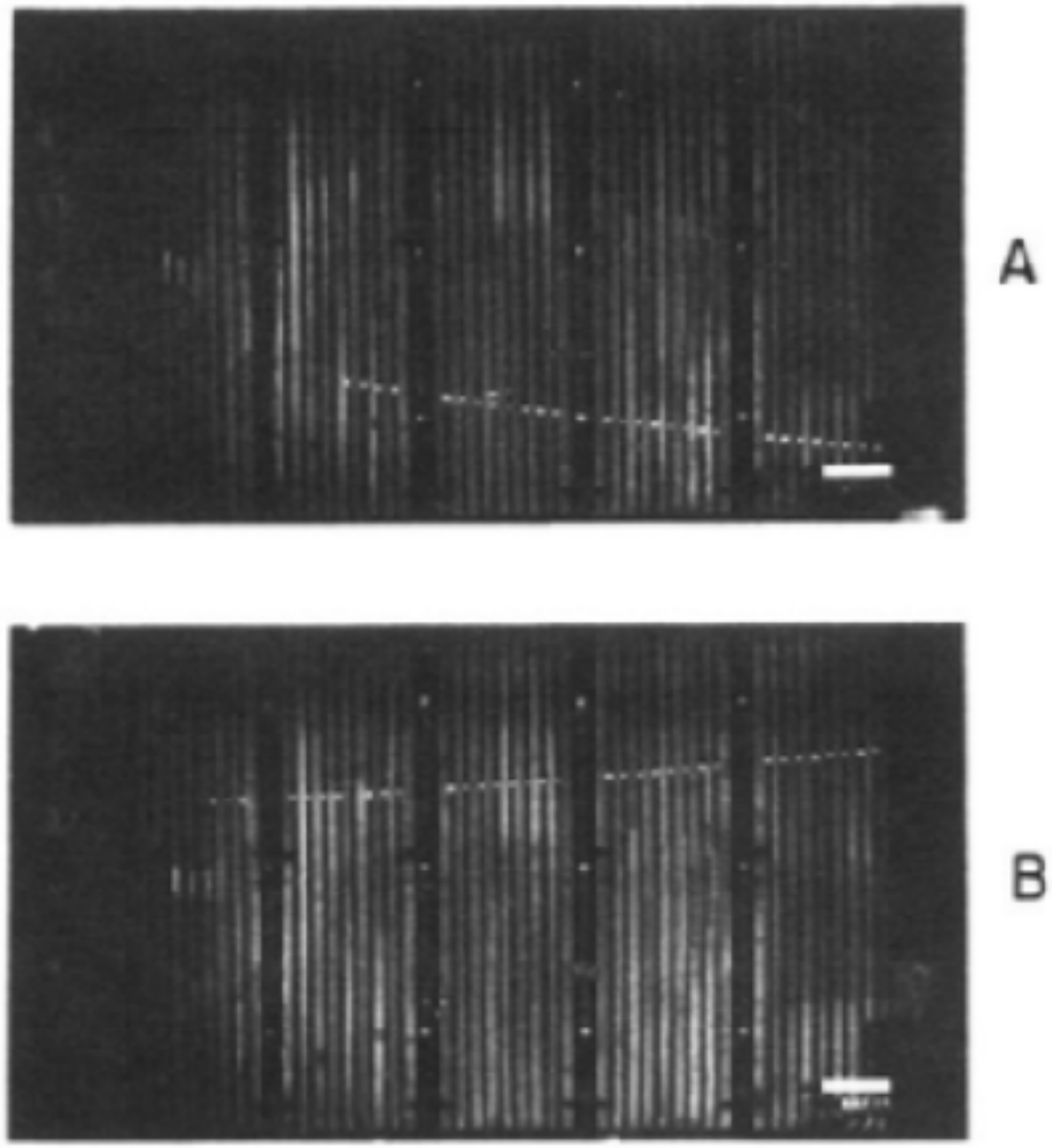
Nr. 20 6500 × 100 3/54



A brief history of the 3 neutrinos

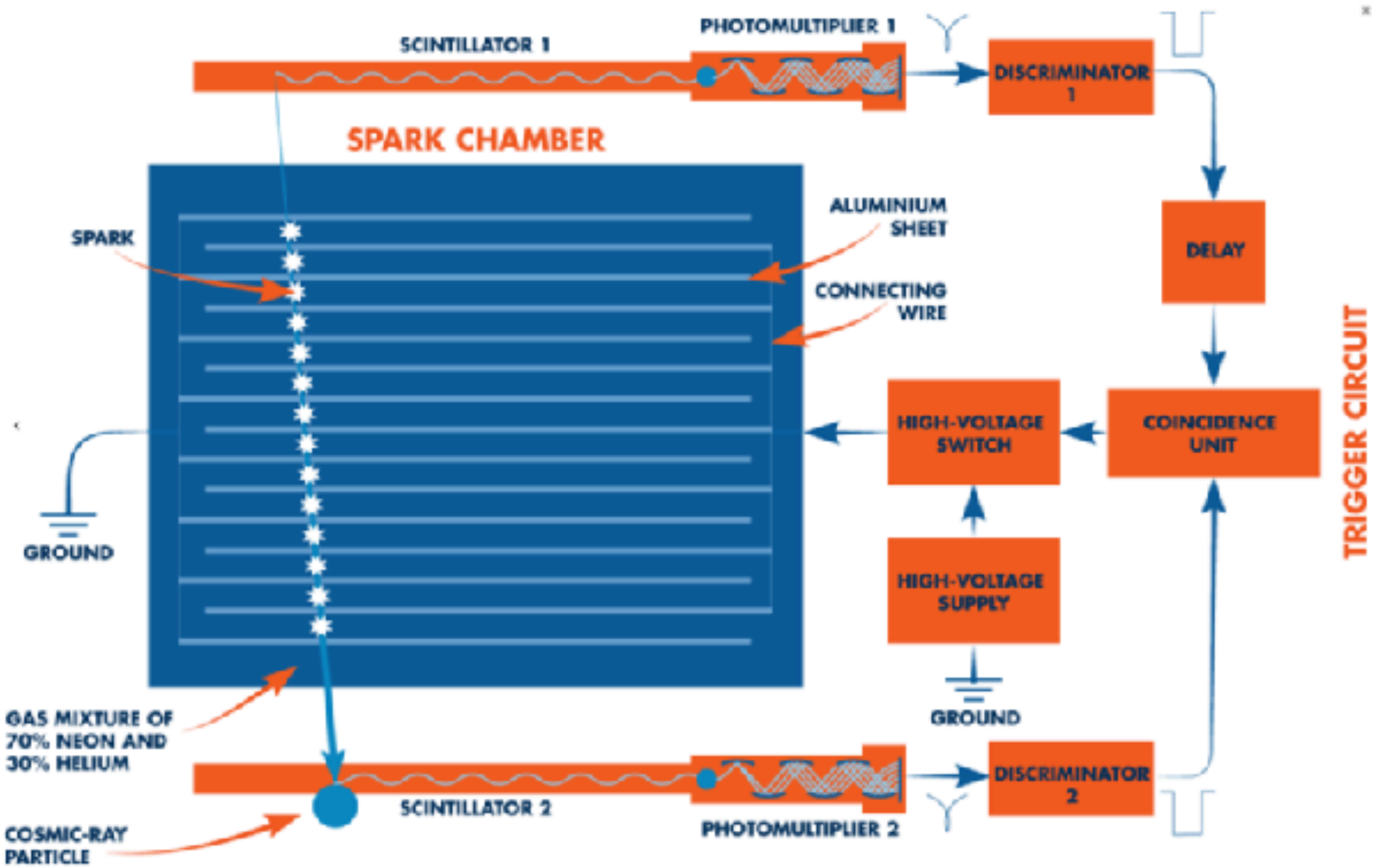
- ν_μ discovery in 1962 by Lederman, Shwartz, Steinberg (Nobel 1988)

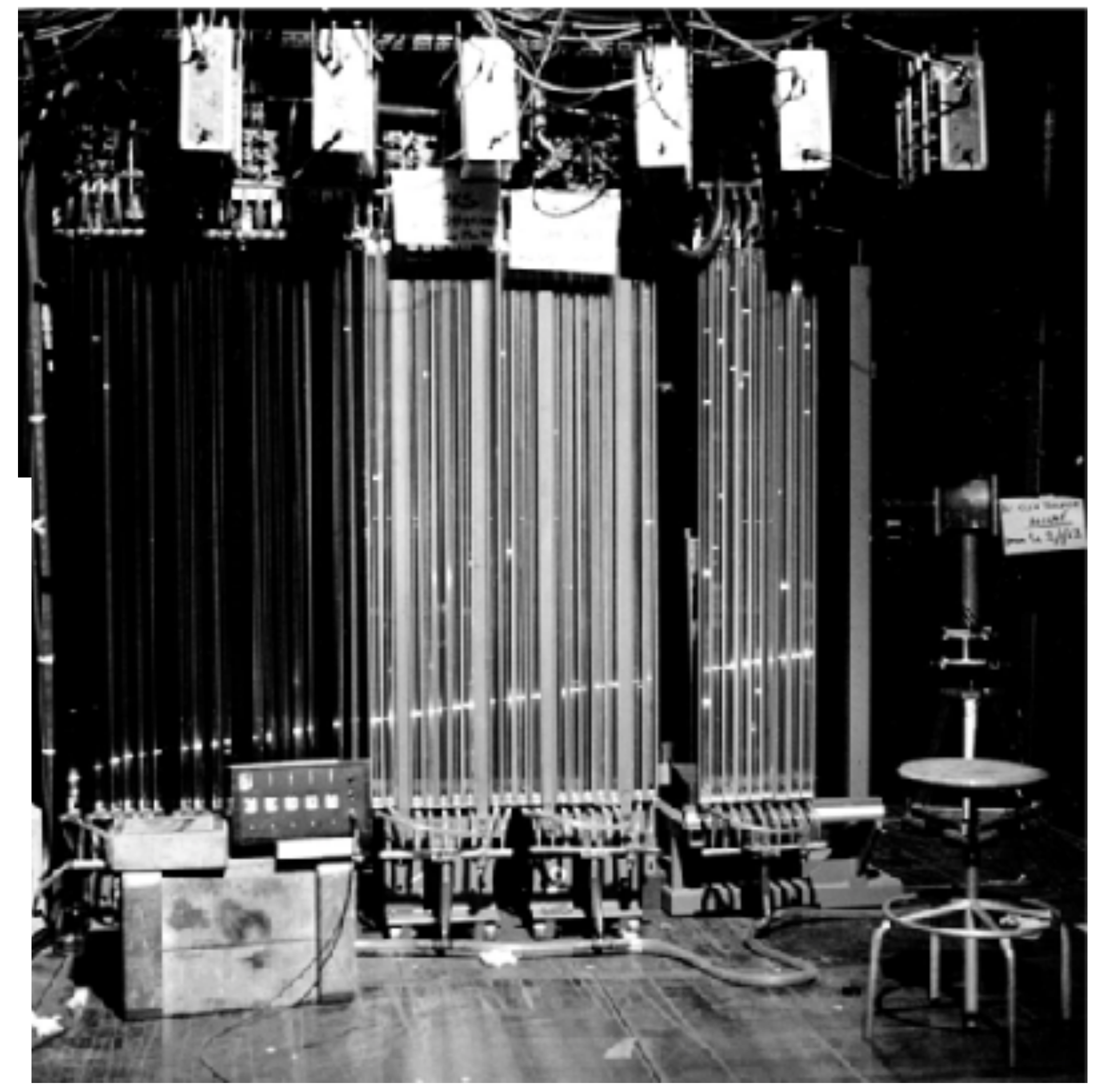




A brief history of the 3 neutrinos

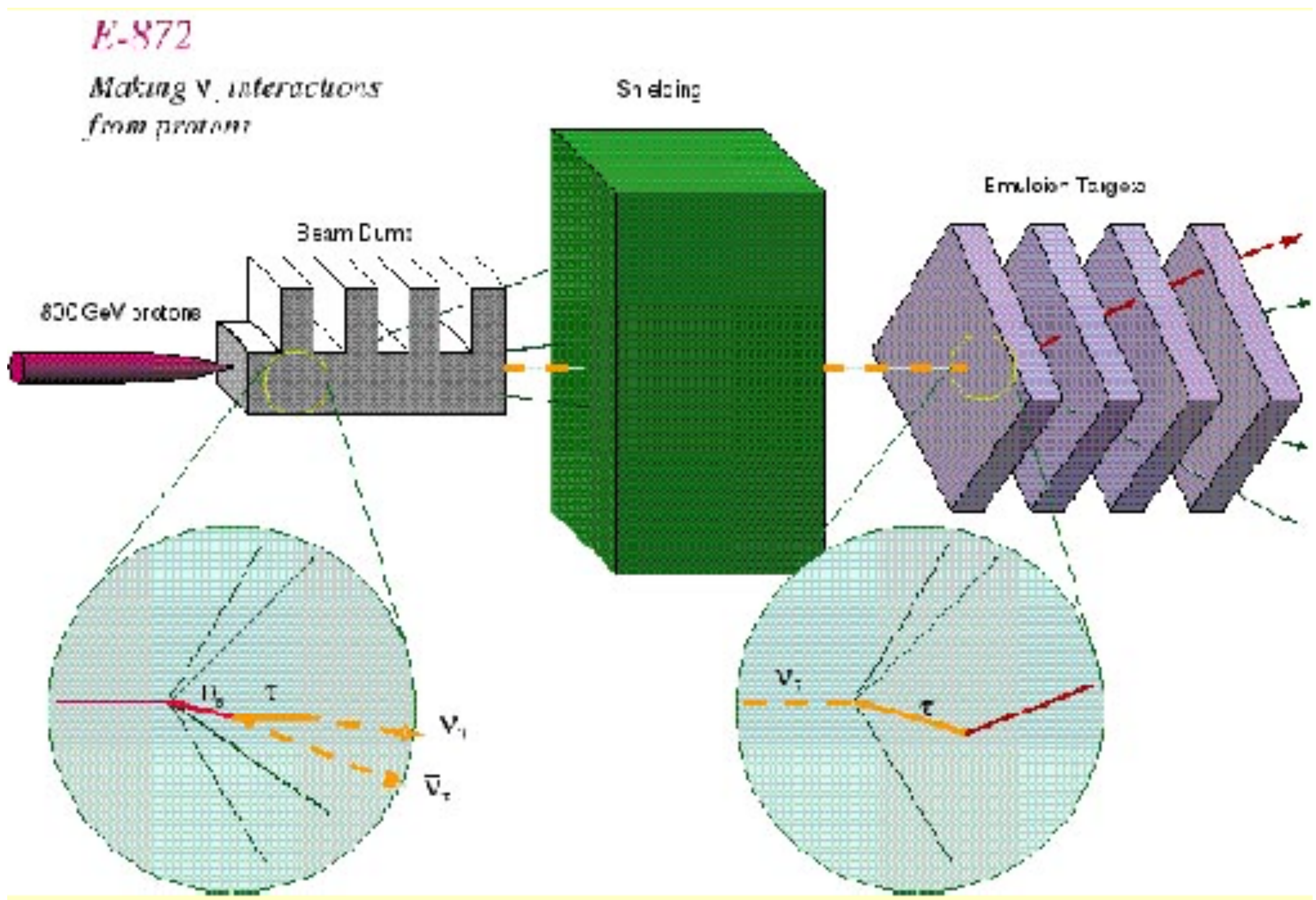
- ν_μ discovery in 1962 by Lederman, Shwartz, Steinberg (Nobel 1988)





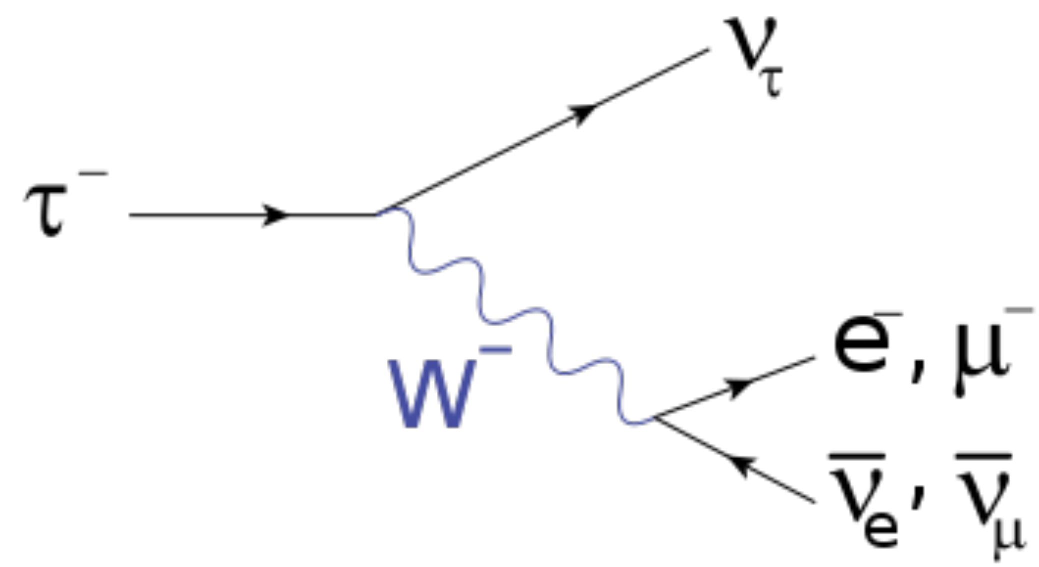
A brief history of the 3 neutrinos

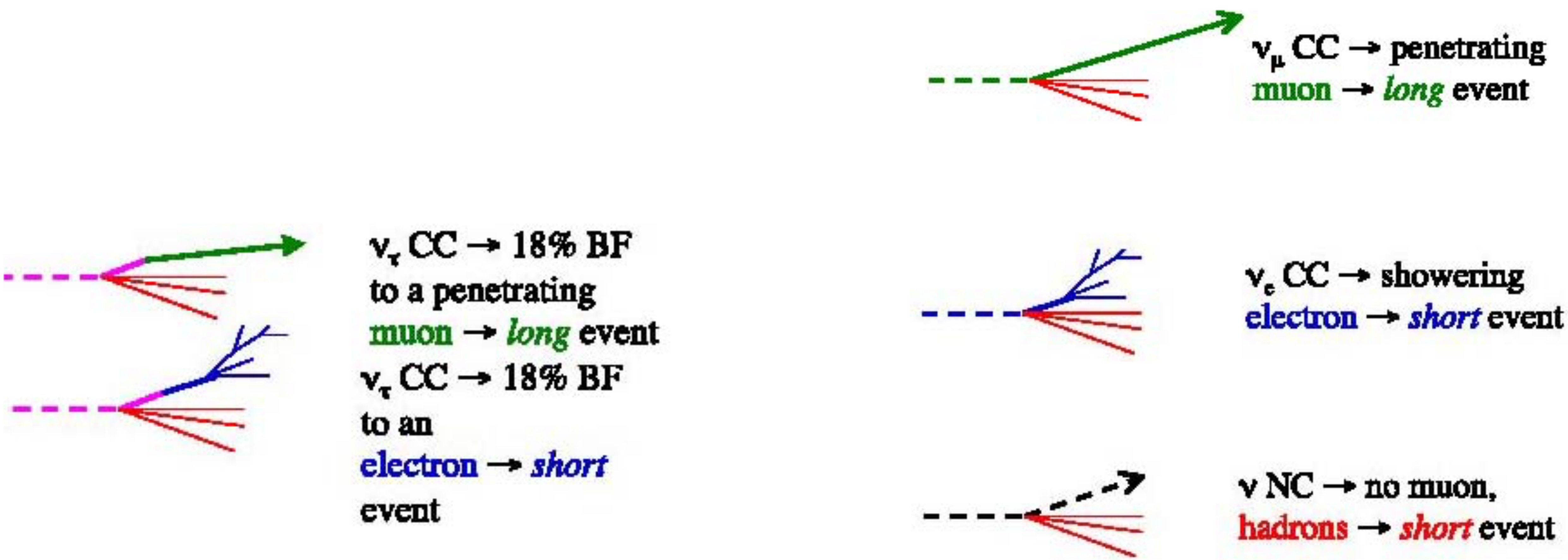
- ν_τ discovery in 2000 by DONUT experiment (FNAL)



A brief history of the 3 neutrinos

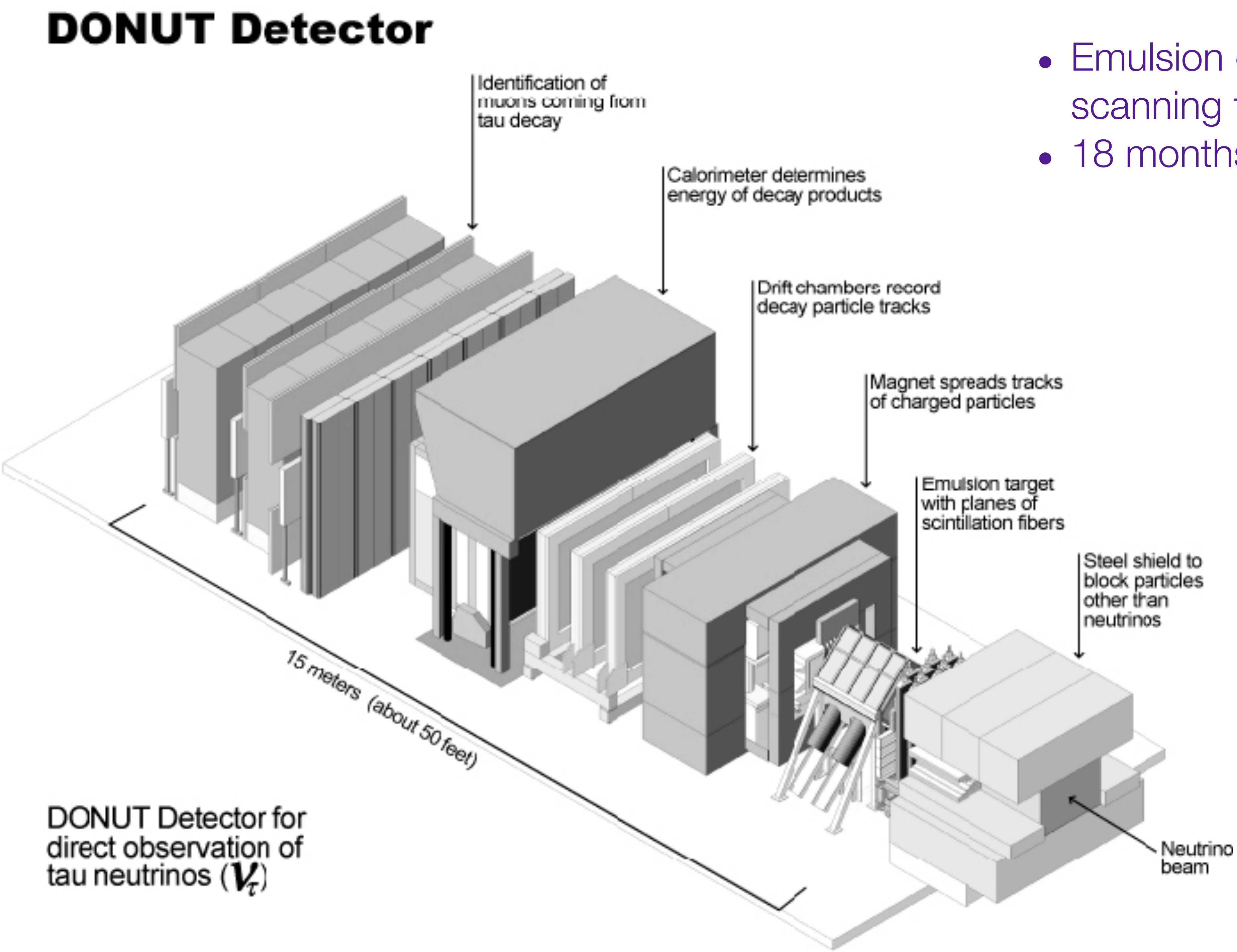
- ν_τ discovery in 2000 by DONUT experiment (FNAL)





A brief history of the 3 neutrinos

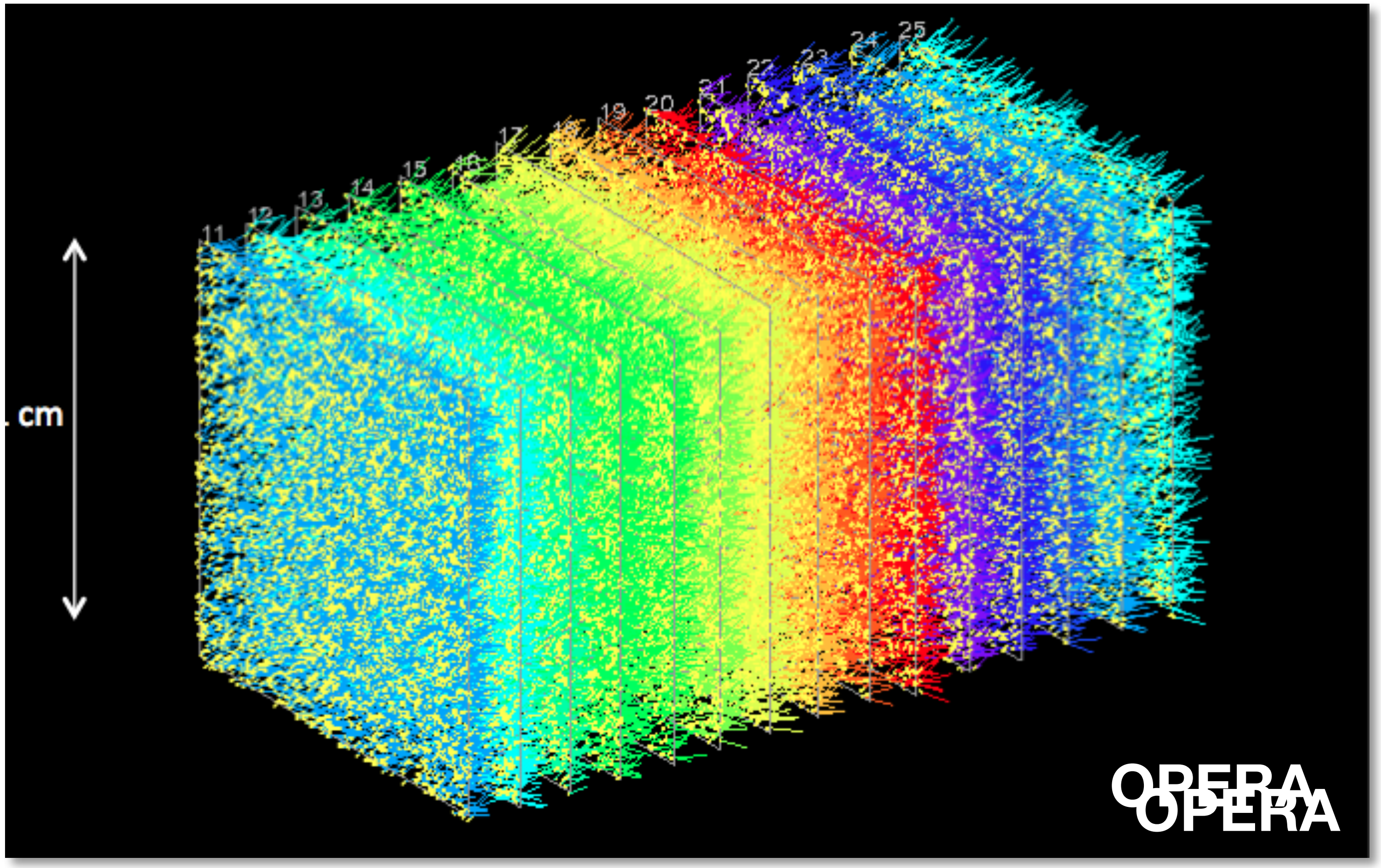
- ν_τ discovery in 2000 by DONUT experiment (FNAL)



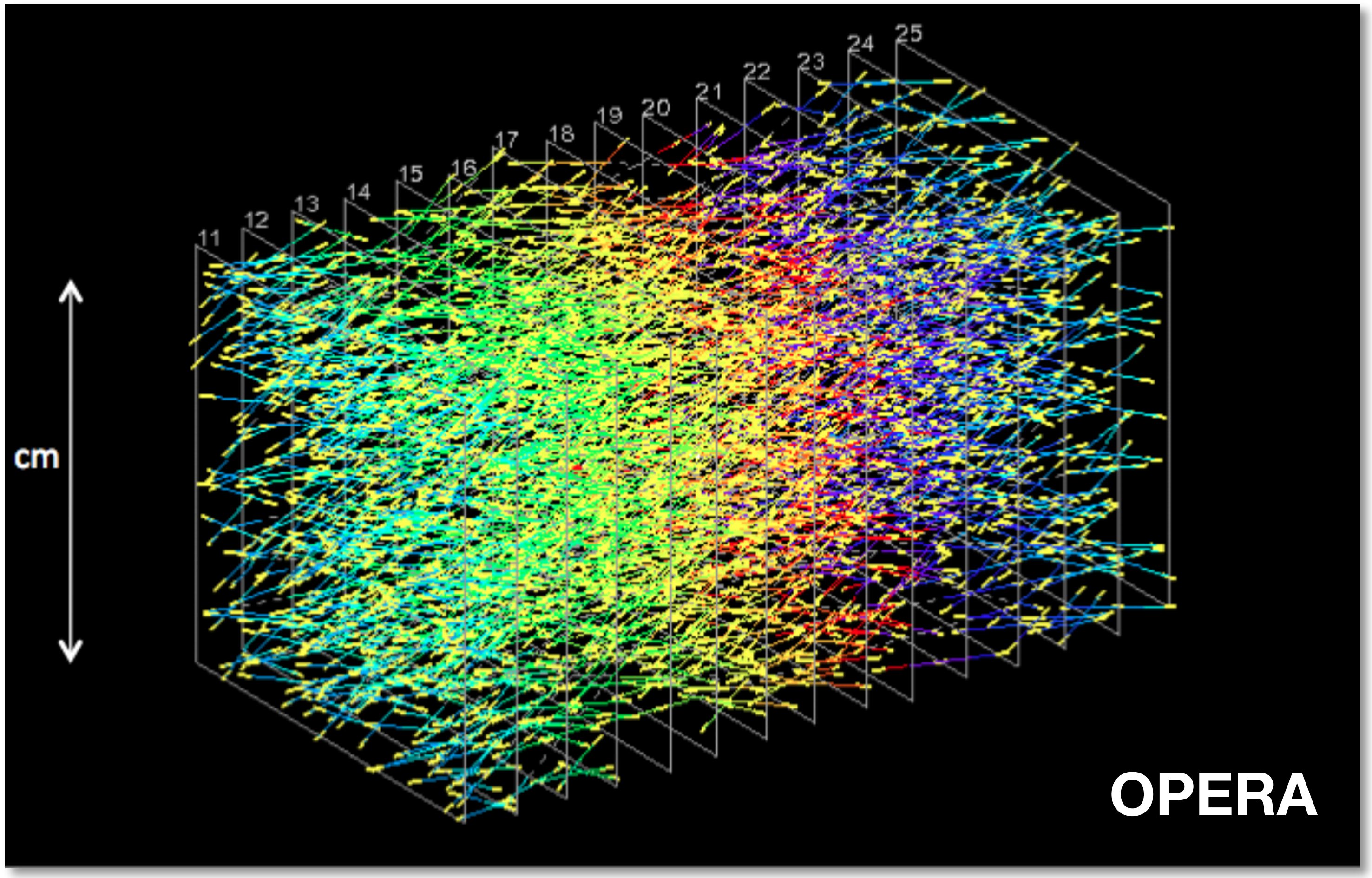
- Emulsion data processed by "digital scanning techniques"
- 18 months to process data!

Phy. Rev. D 78, 052002 (2008)

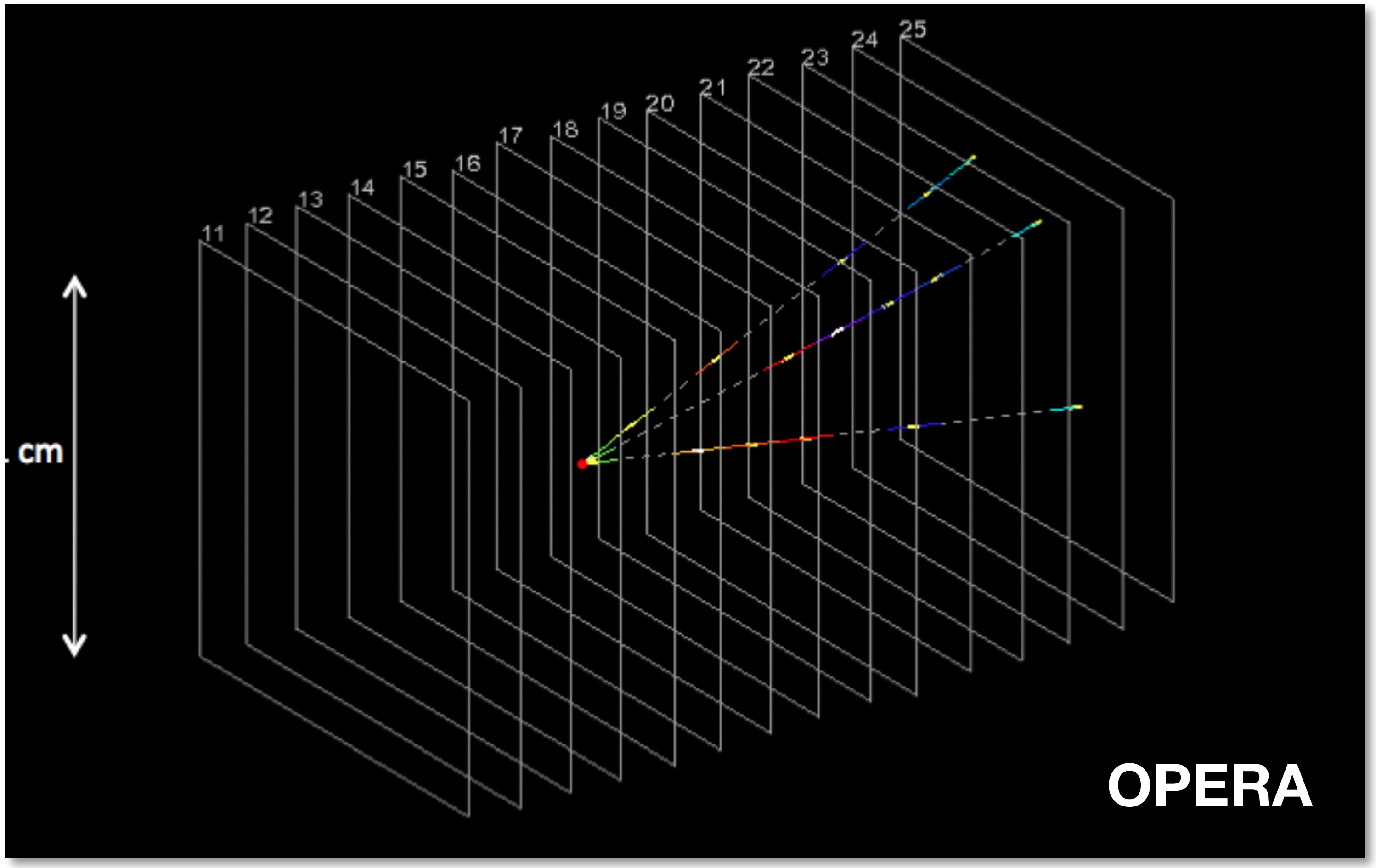
Finding the ν_τ



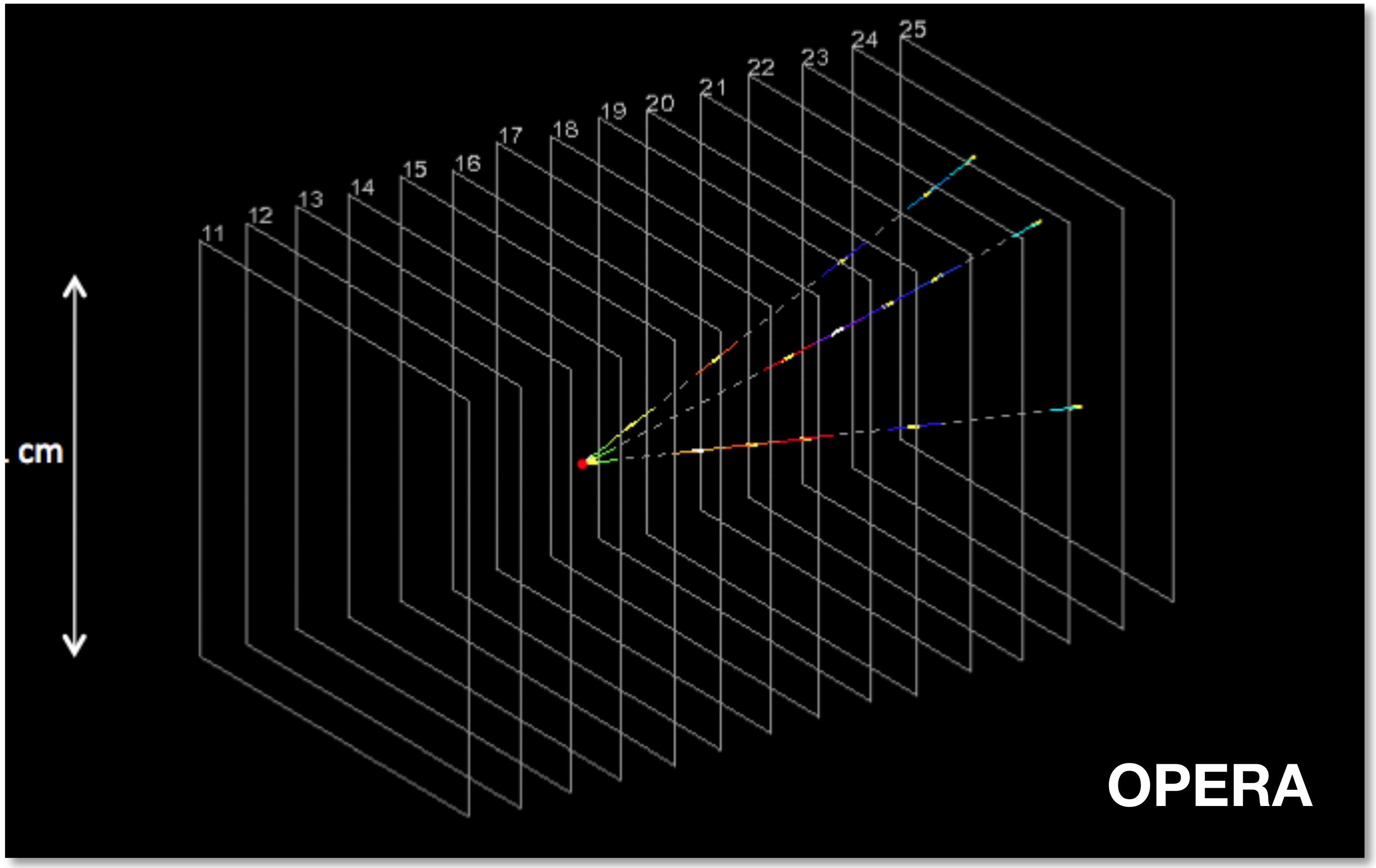
Finding the ν_τ



Finding the ν_τ



Finding the ν_τ



9 ν_τ detected!

Phy. Rev. D 78, 052002 (2008)

Neutrinos and the Standard Model

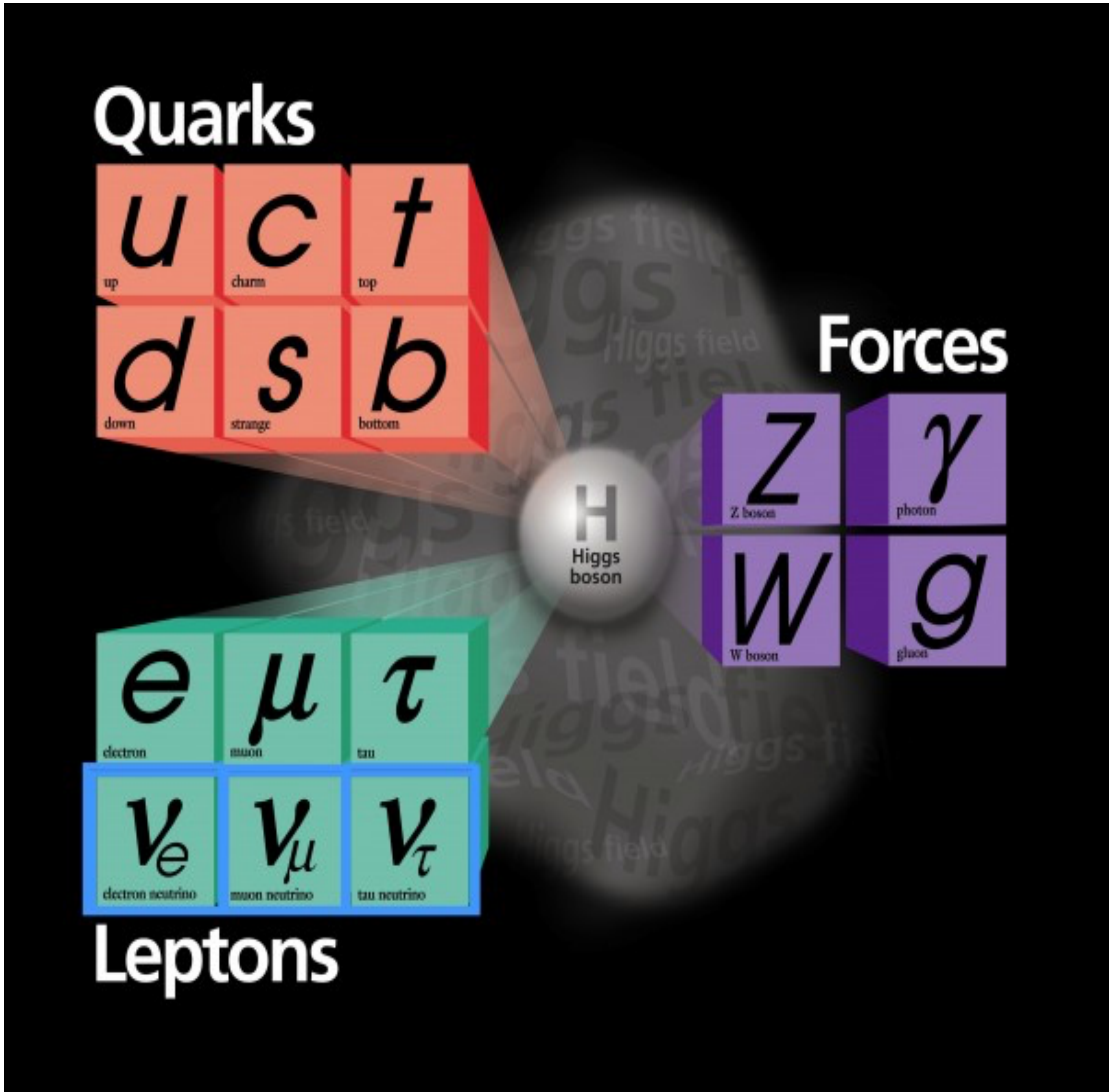
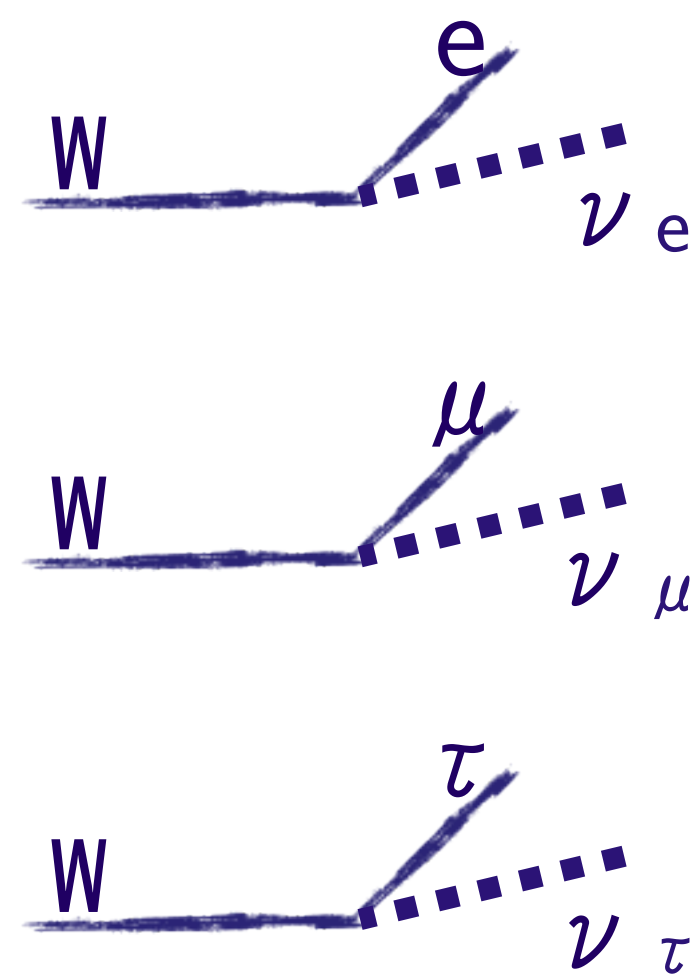


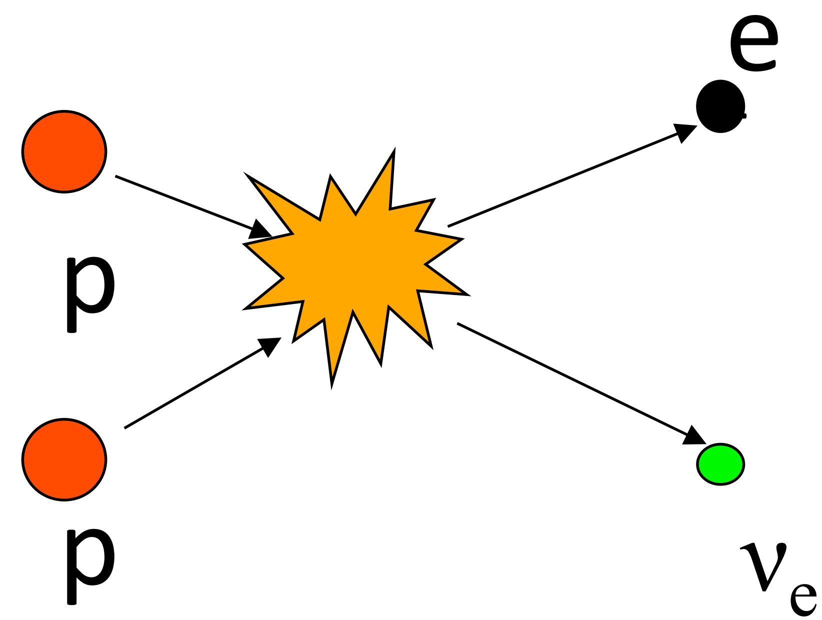
image credit: FNAL

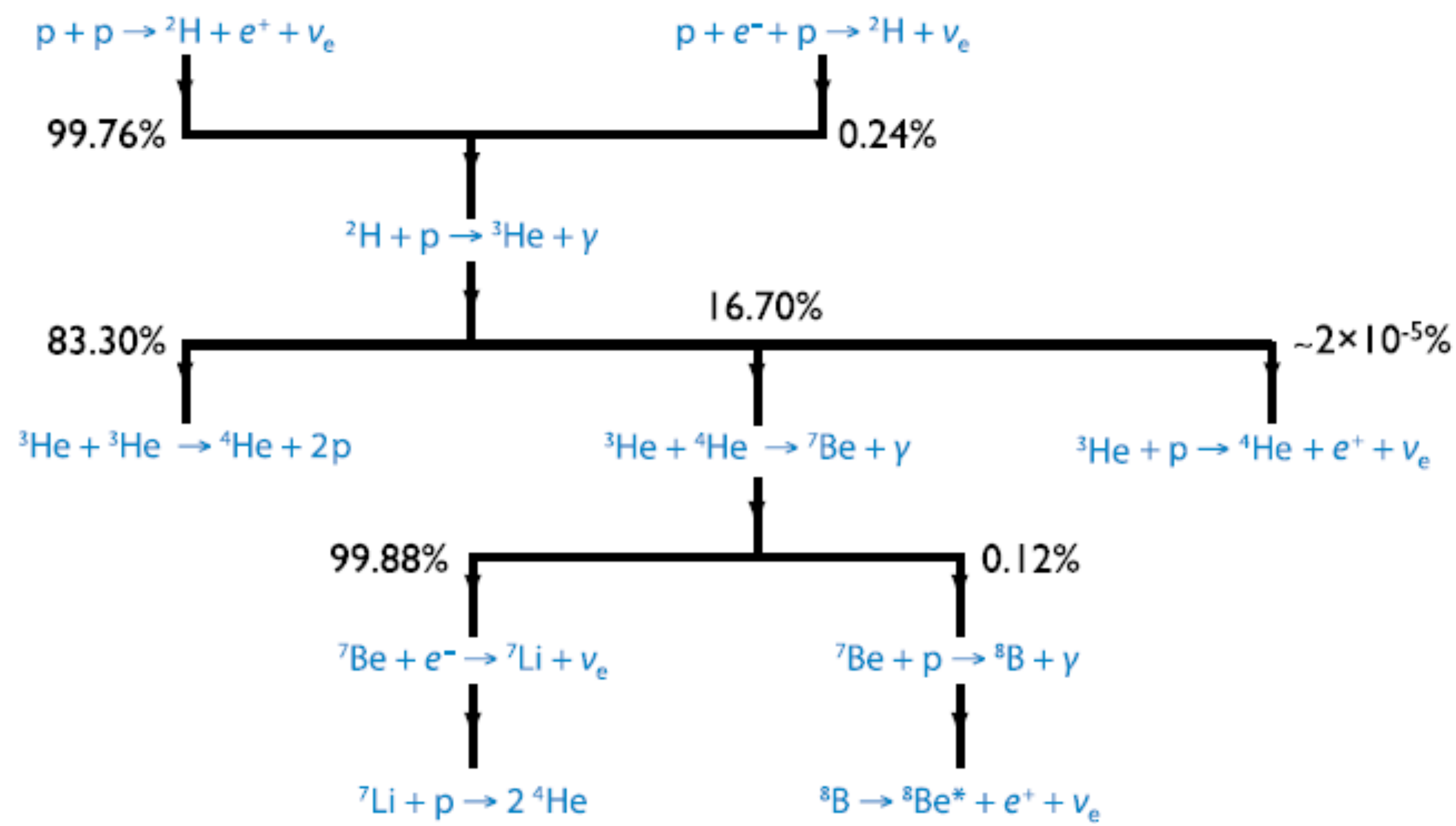
- Three flavours
- Weak interaction only
- zero-mass



Solar neutrinos

- In 1960's, physicists had a good understanding of the sun fusion model
- pp and pep fusion
- Predictions for the neutrino flux by Bachall
- Await experimental confirmation





Solar neutrino detector

- In 1964, Ray Davis build a large neutrino detector
- 380 000l of perchloroethylene (cleaning fluid!)
- Neutrino interaction: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Number of ^{37}Ar $\propto$ to number of ν_e
- Results gave ~10 atoms of ^{37}Ar every months
- This was 1/3 of theoretical predictions

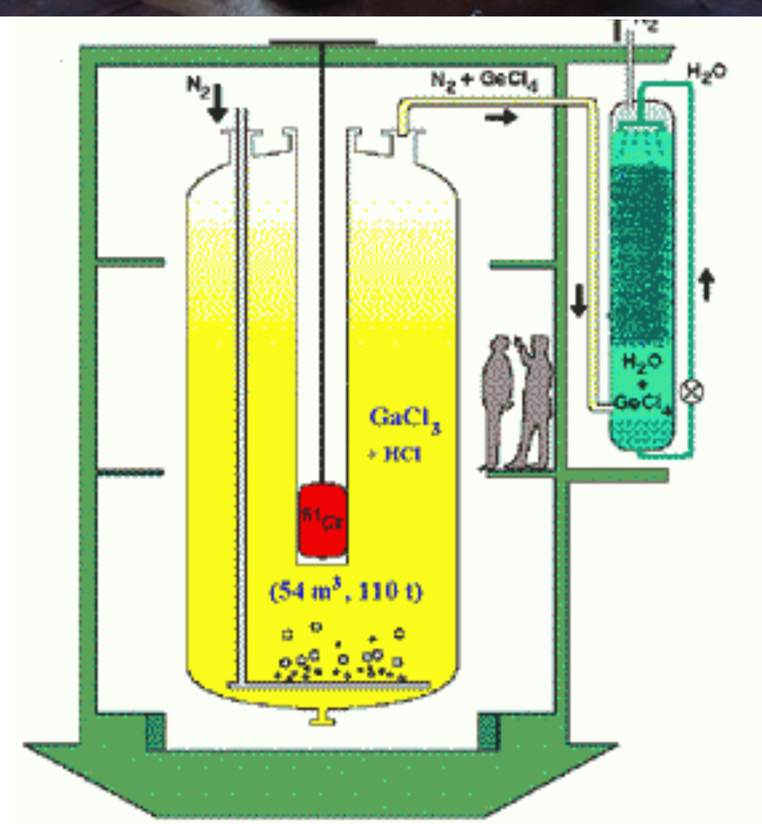
Solar neutrino detector

- In 1964, Ray Davis build a large neutrino detector
- 380 000l of perchloroethylene (cleaning fluid!)
- Neutrino interaction: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Number of $^{37}Ar \propto$ to number of ν_e
- Results gave ~10 atoms of ^{37}Ar every months
- This was 1/3 of theoretical predictions

Solar Neutrino Problem!

Follow-up solar neutrino experiments

Two experiments used to address Davis' results: Gallex (1991) and Kamiokande II (1985)



Gallex

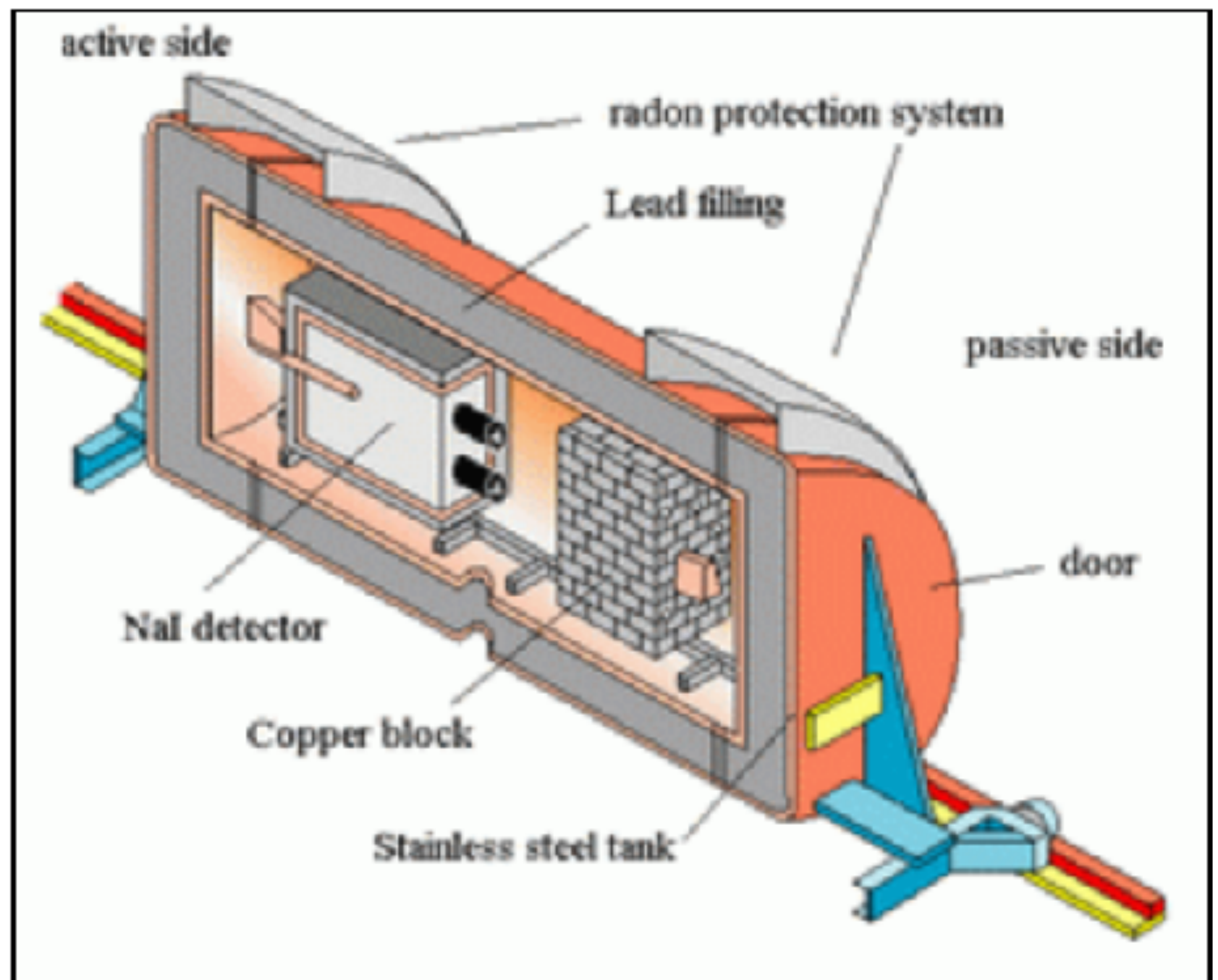
KamiokaNDE:
Kamioka Nucleon Decay Experiment

Follow-up solar neutrino experiments

30 ton of Galium

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

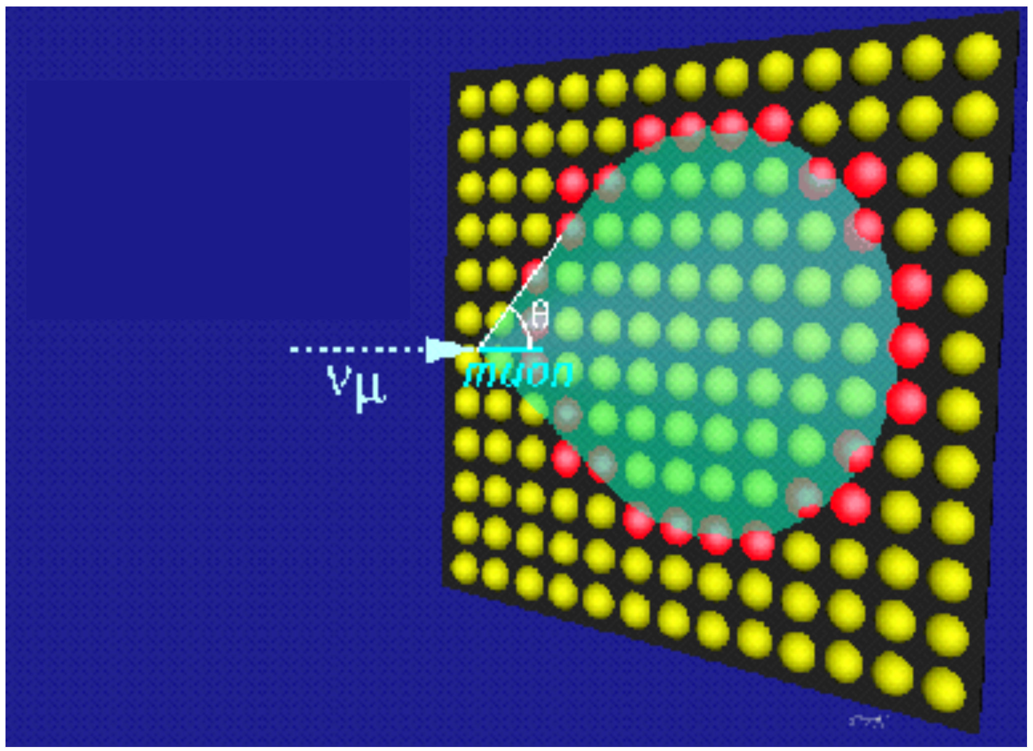
Very similar approach to Davis



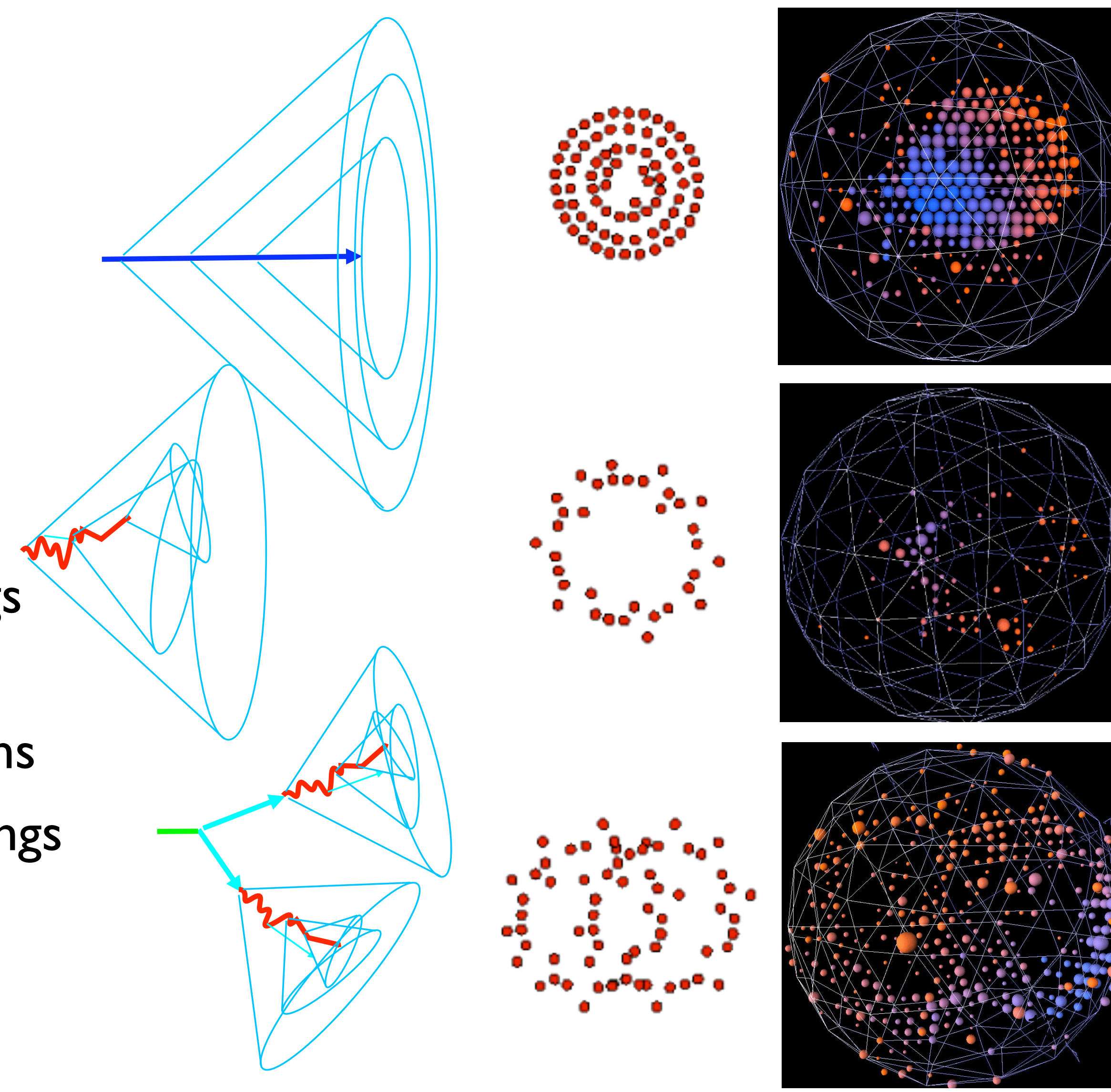
Gallex

Follow-up solar neutrino experiments

Two experiments used to address Davis' results: Gallex (1991) and

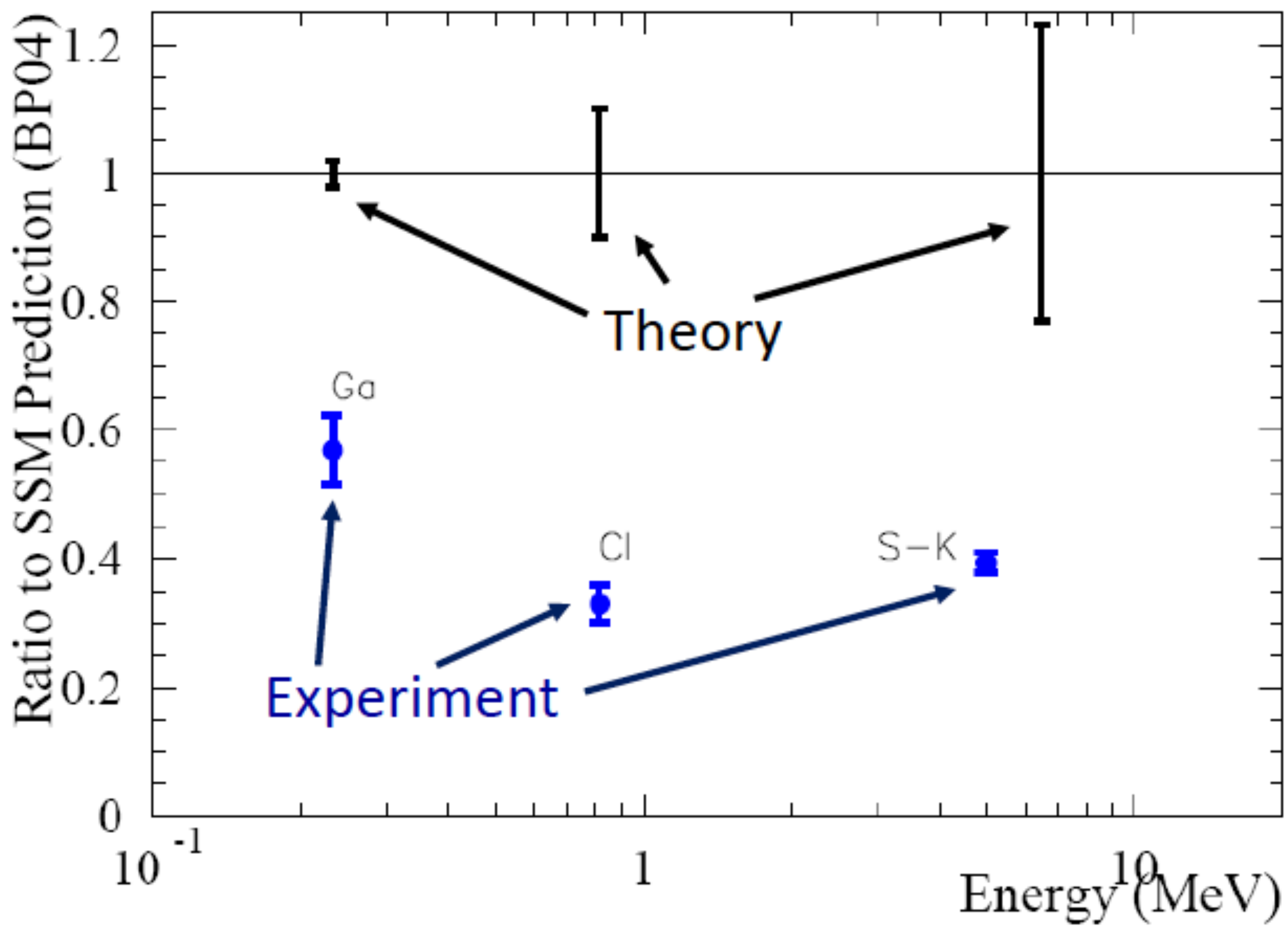


- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings



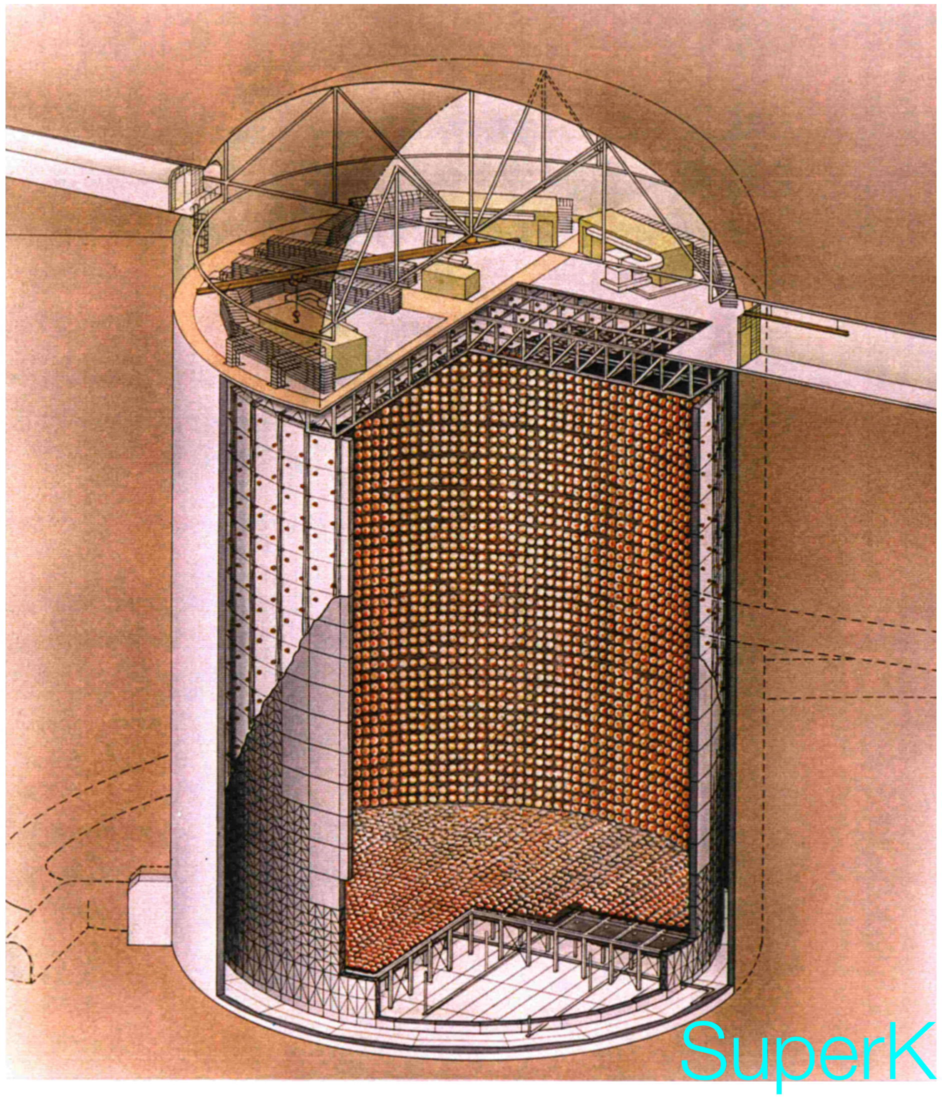
Follow-up solar neutrino experiments

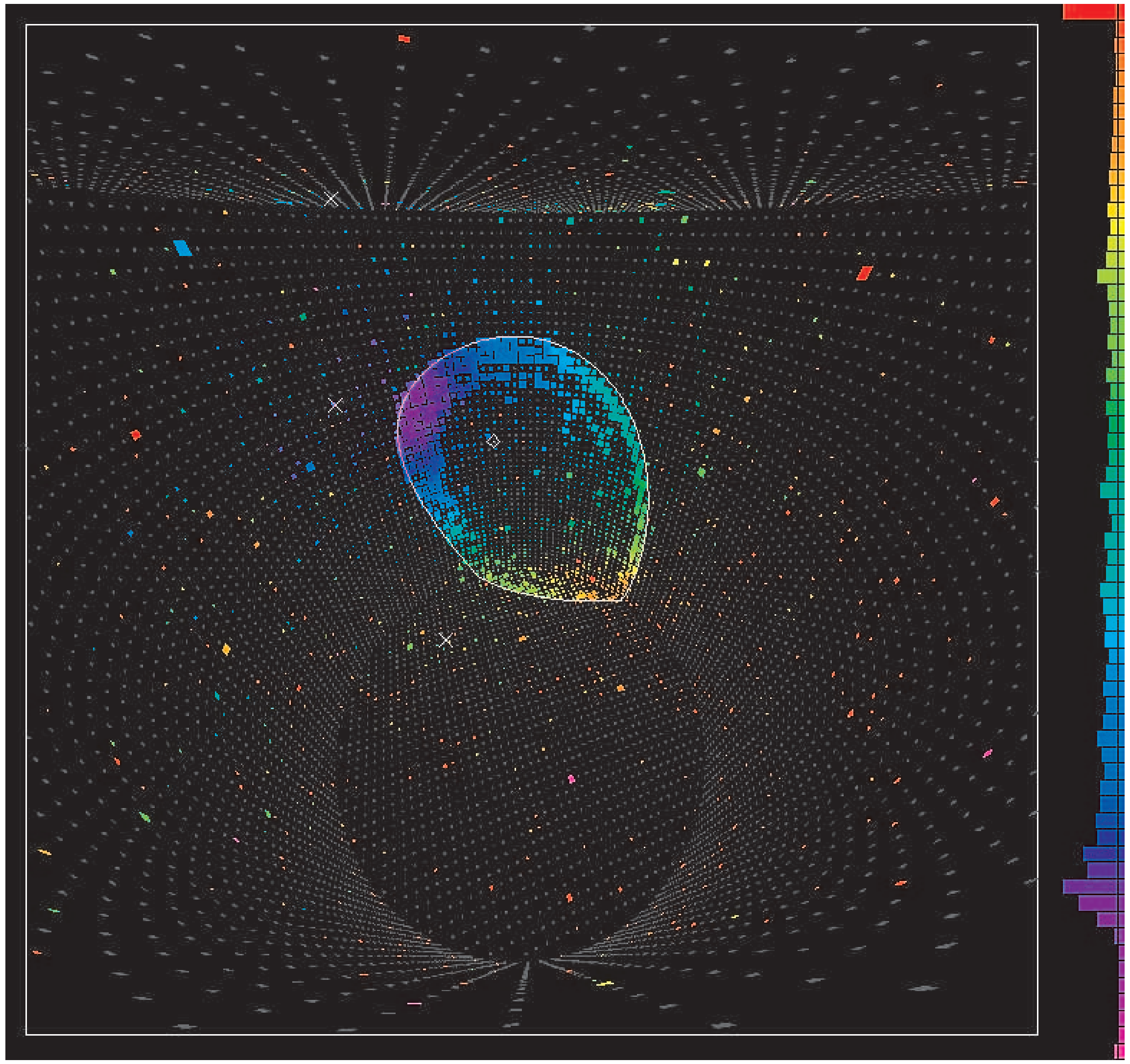
Two experiments used to address Davis' results: Gallex (1991) and Kamiokande II (1985)



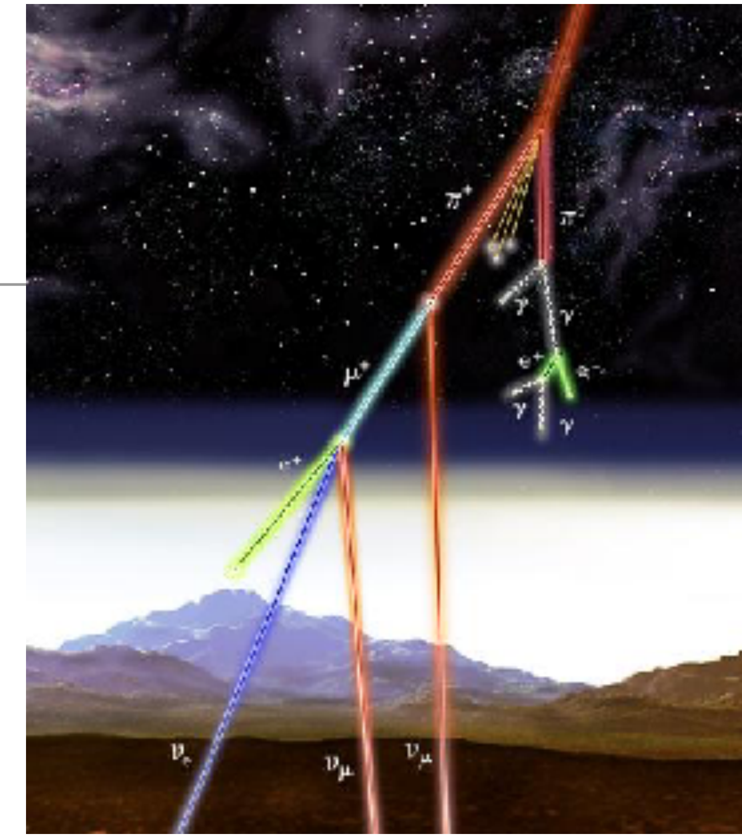
Neutrino oscillations?

- SuperKamiokande experiment

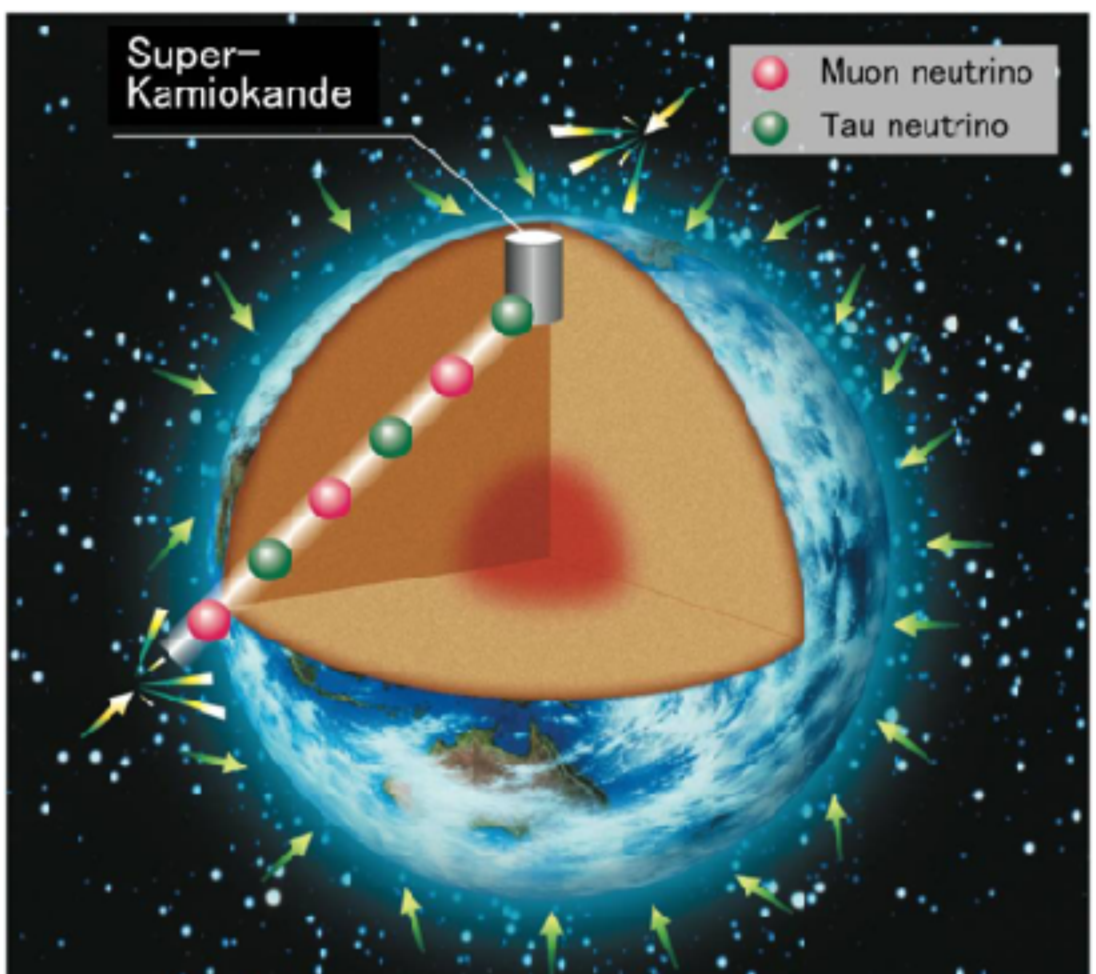


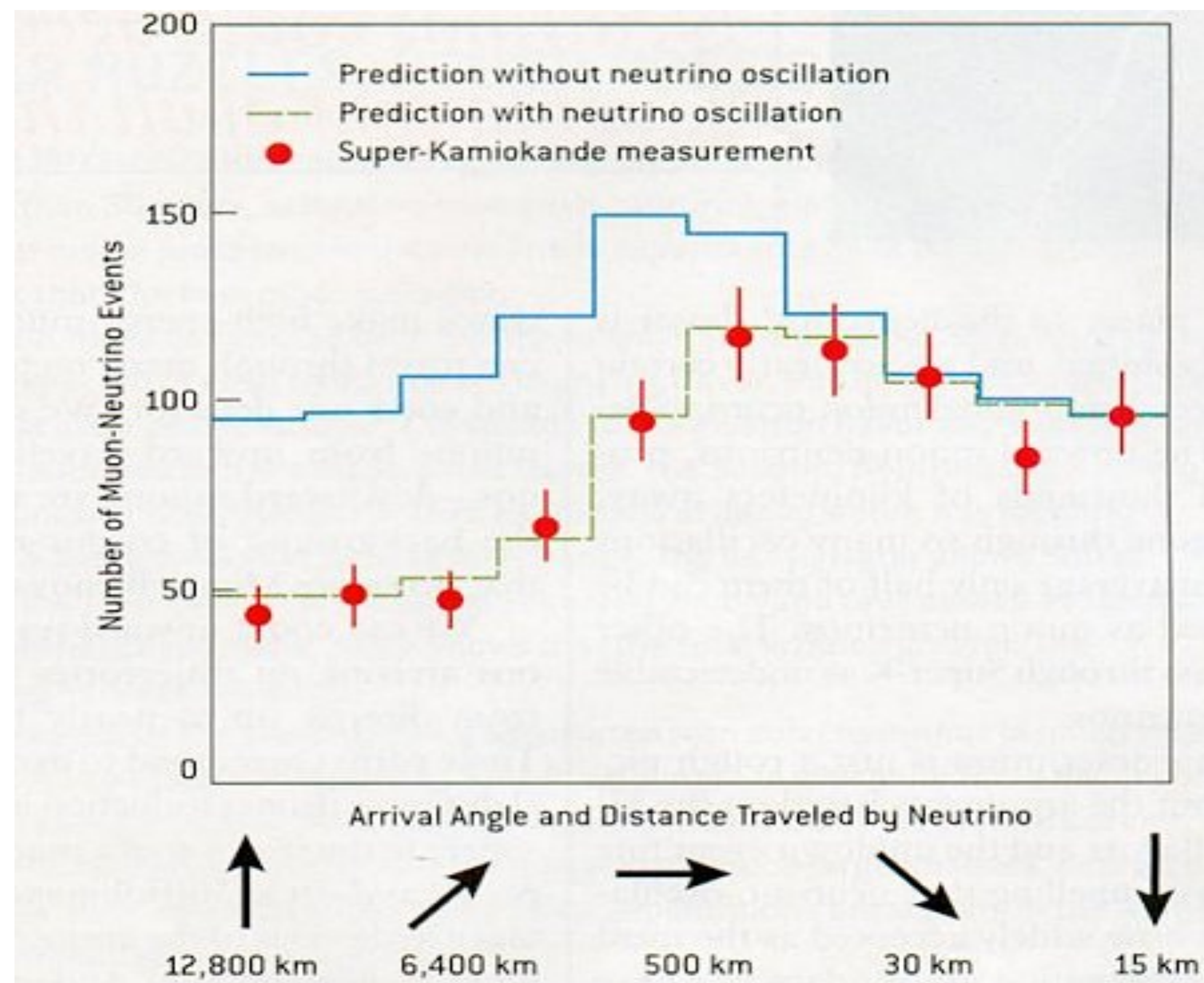


Neutrino oscillations!



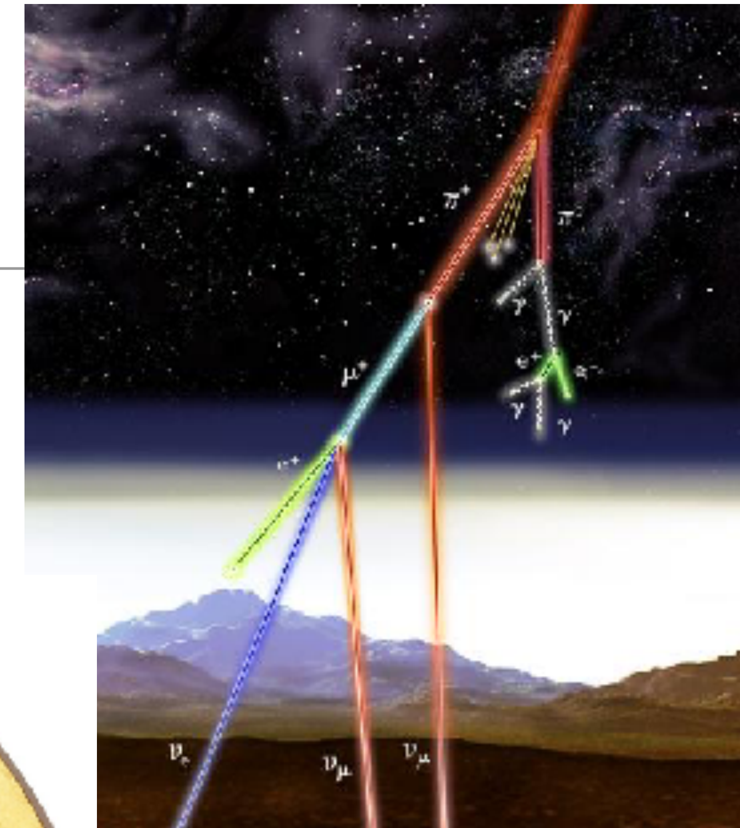
- SuperKamiokande experiment
- Atmospheric neutrino detection
- 1998 -> Discovery!

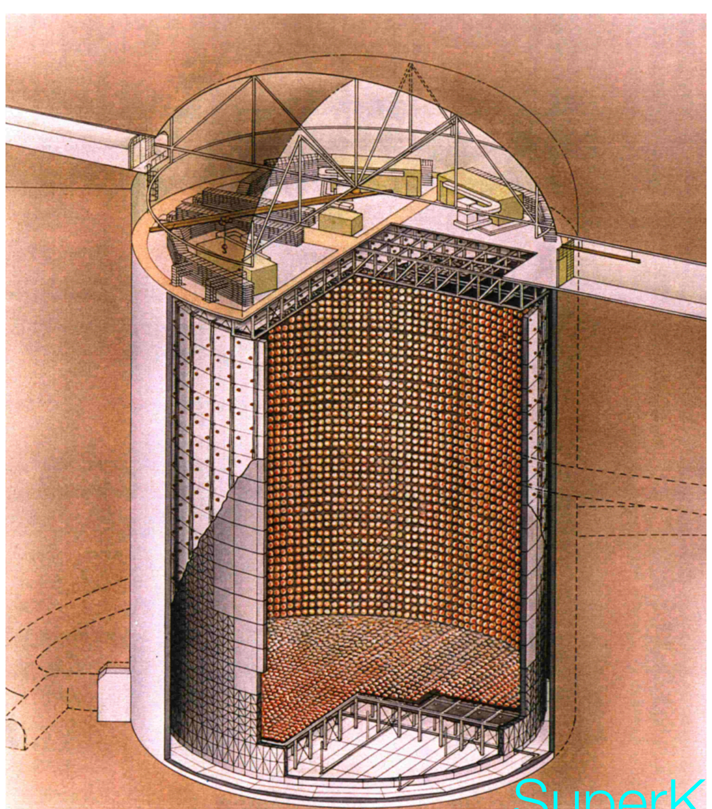


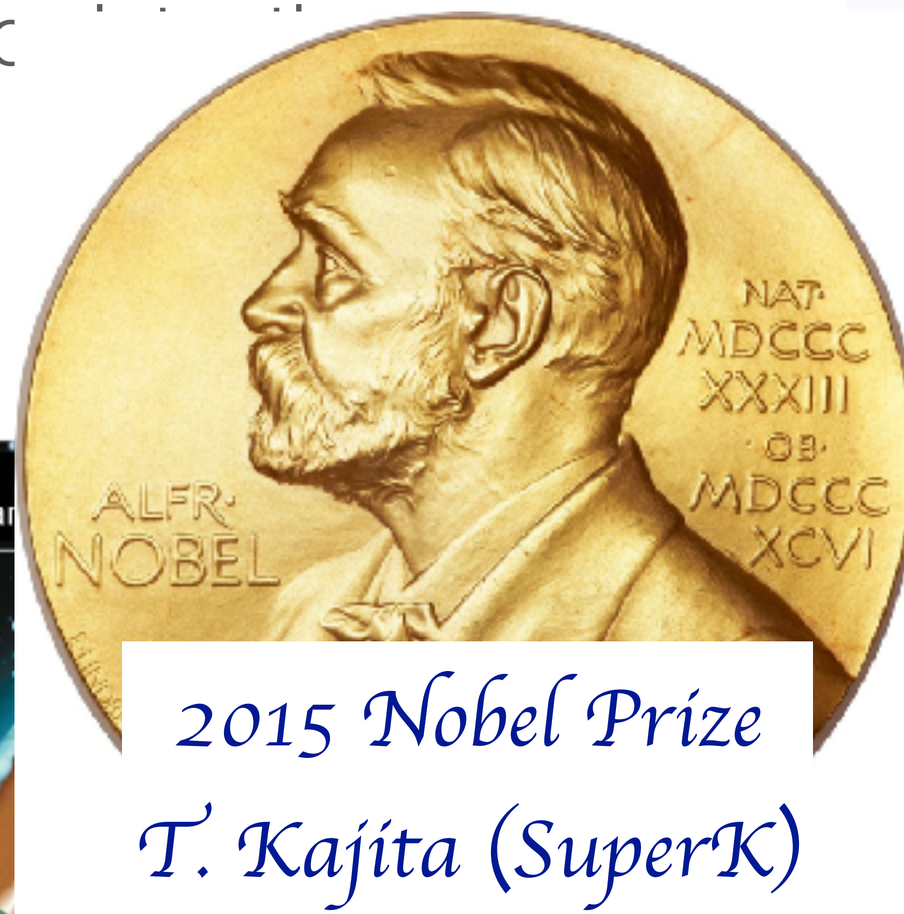


Neutrino oscillations!

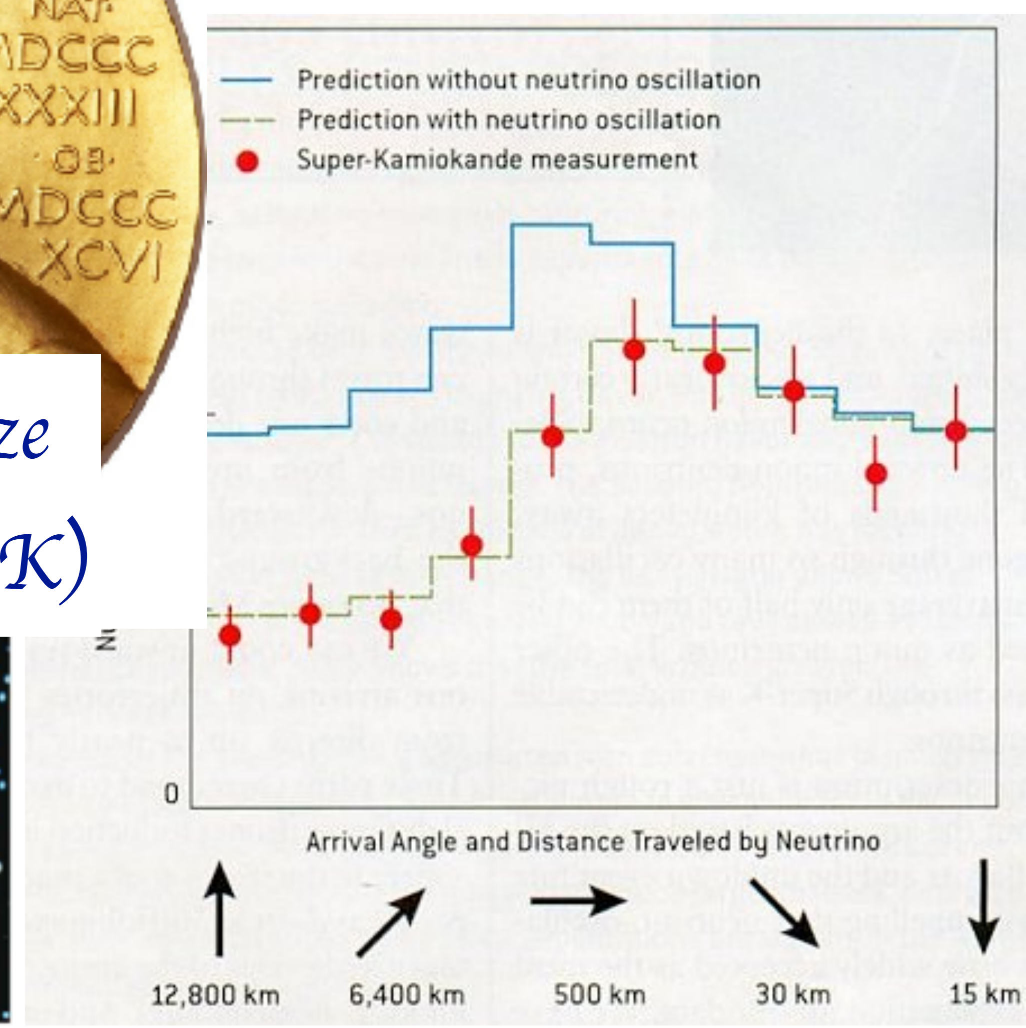
- SuperKamiokande experiment
- Atmospheric neutrinc
- 1998 -> Discovery!





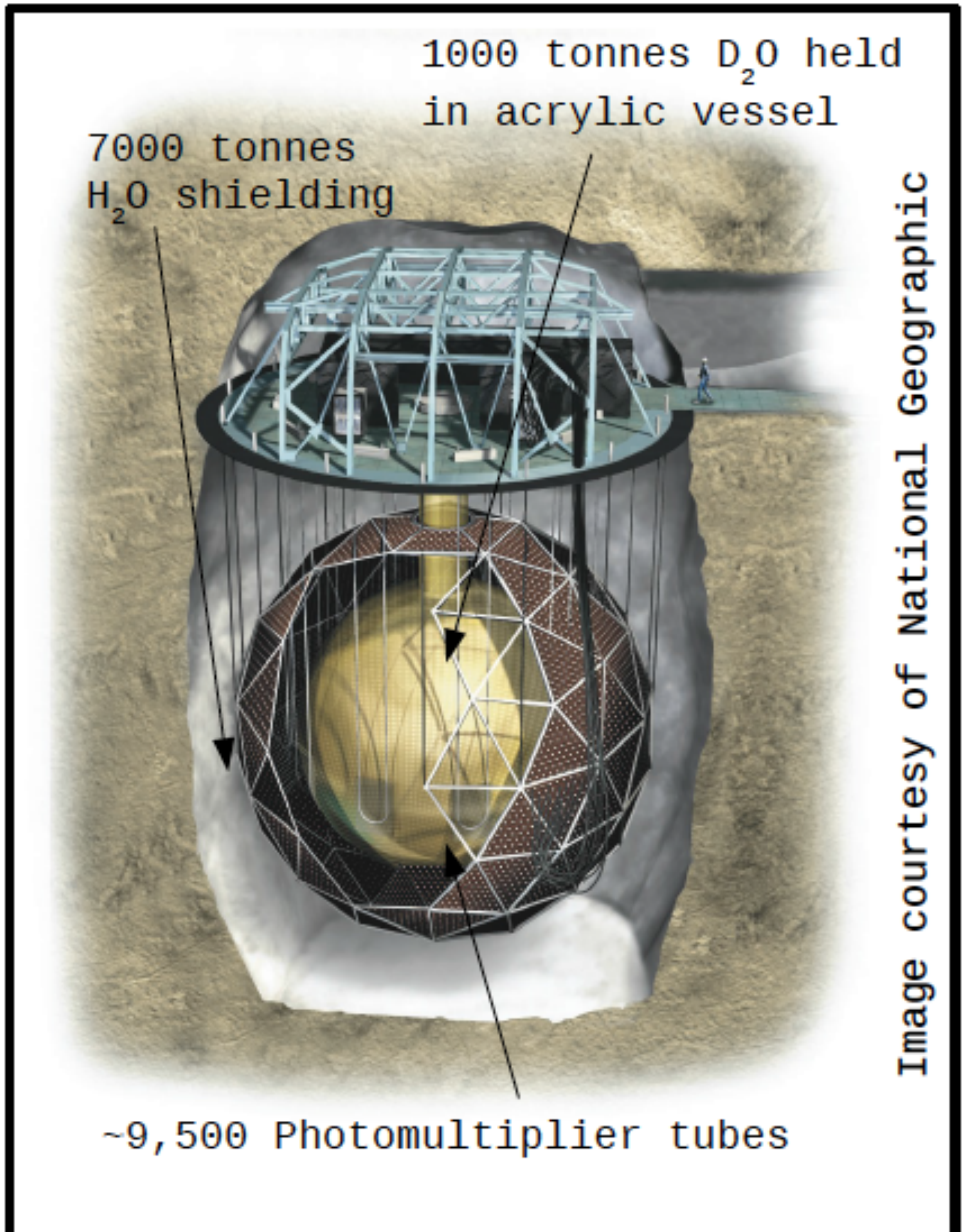


2015 Nobel Prize
T. Kajita (SuperK)



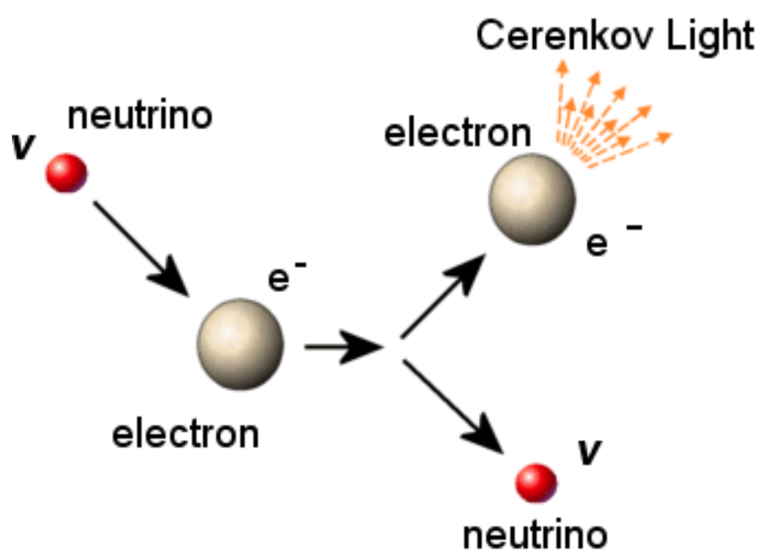
Neutrino oscillations and the solar neutrino problem

SNO experiment (1999 - 2008)



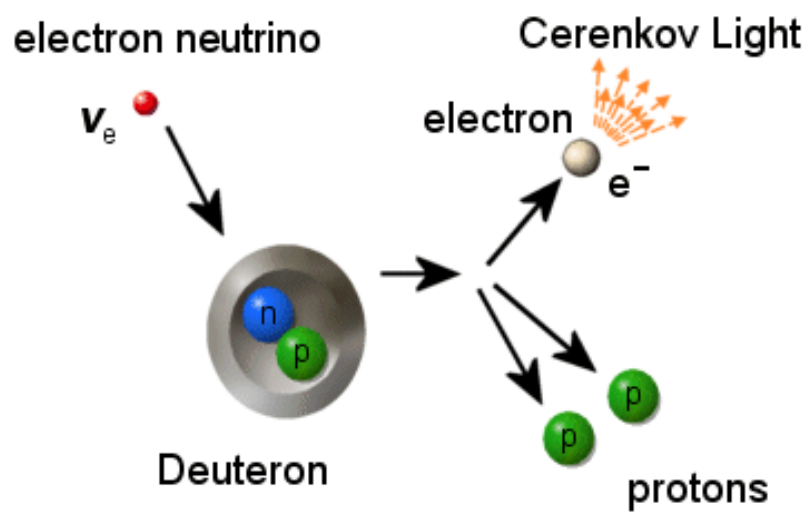
Neutrino oscillations and the solar neutrino problem

SNO experiment (1999 - 2008)



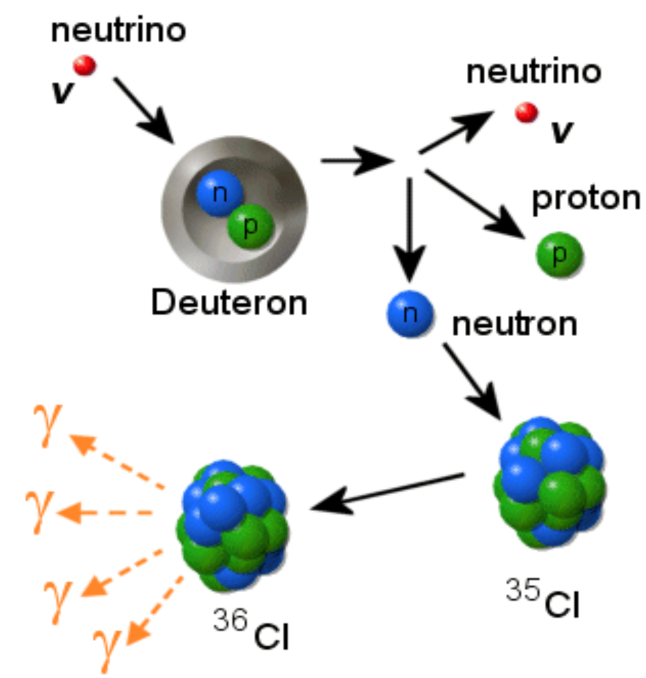
Elastic Scattering

- Sensitive to all flavours
- More sensitive to ν_e
- Gives direction of ν



Charged Current

- Sensitive to only ν_e
- Measures ν energy



Neutral Current

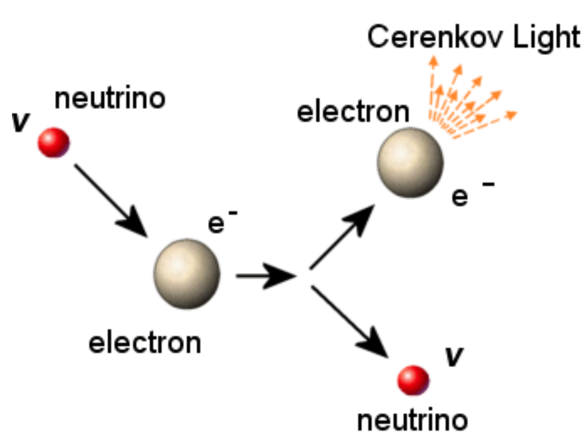
- Equally sensitive to all flavours
- Measures total ^{8}B ν flux

Neutrino oscillations and the solar neutrino problem

SNO experiment (1999 - 2008)

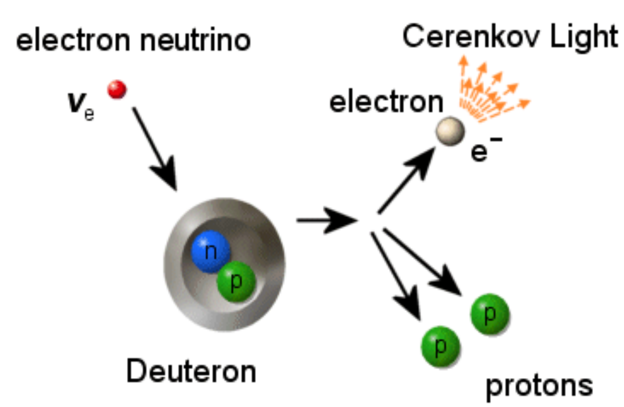
3 phases:

1. Pure D2O (1999-2001)
2. Pure D20 + NaCl (2002-2004)
3. Addition of 3He proportional counters



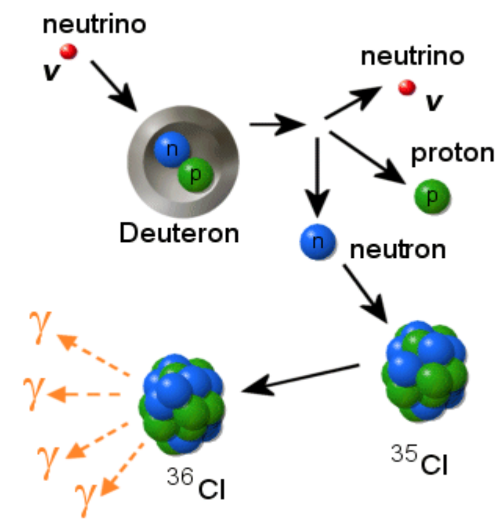
Elastic Scattering

- Sensitive to all flavours
- More sensitive to ν_e
- Gives direction of ν



Charged Current

- Sensitive to only ν_e
- Measures ν energy

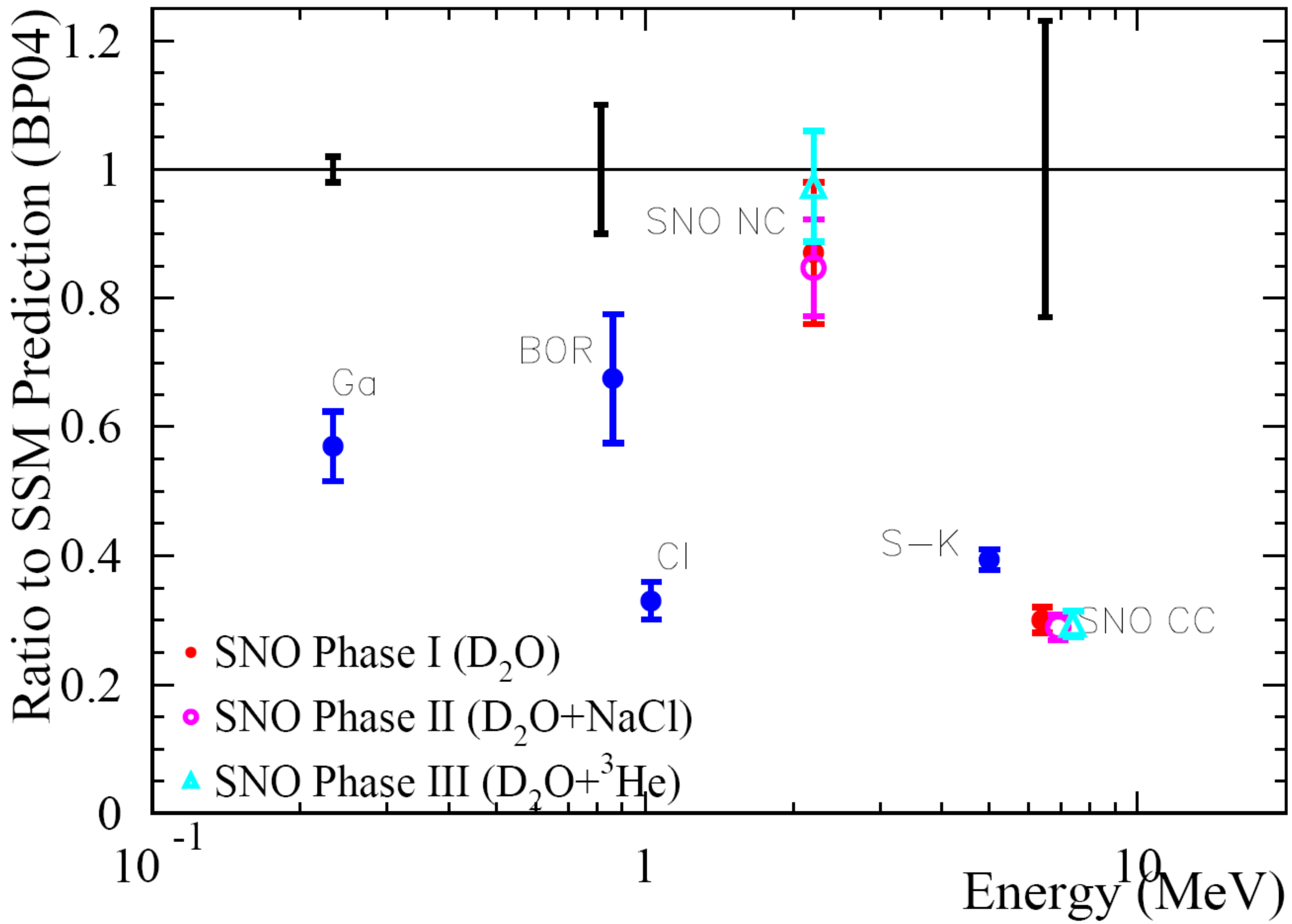


Neutral Current

- Equally sensitive to all flavours
- Measures total ^8B ν flux

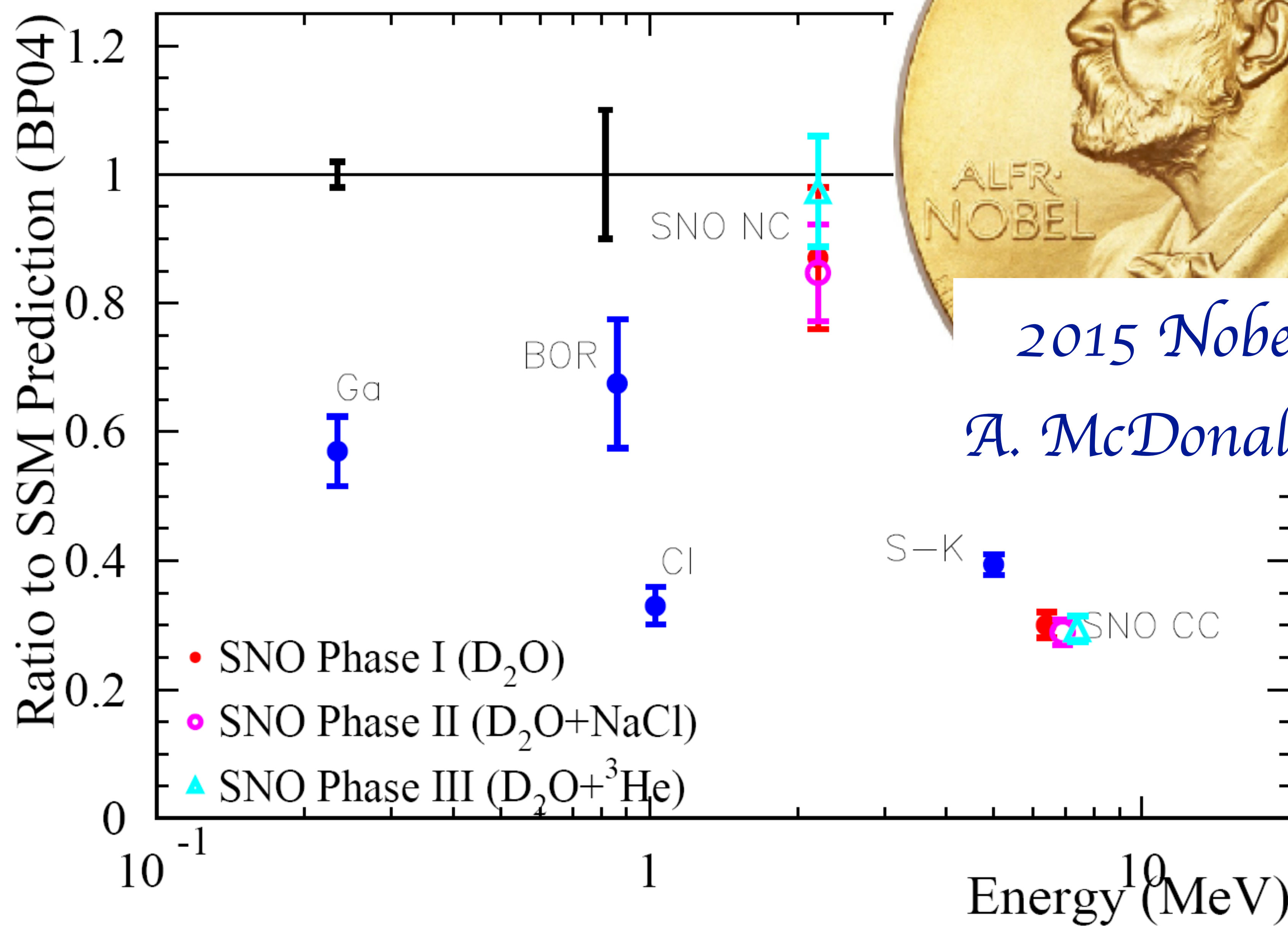
Neutrino oscillations and the solar neutrino problem

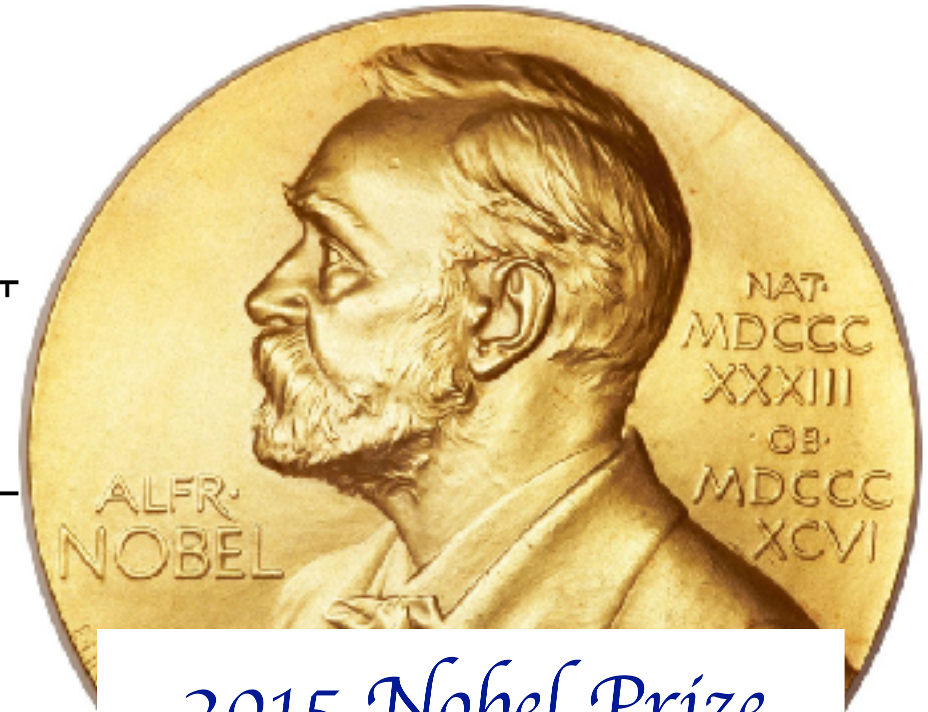
SNO results



Neutrino oscillations and the solar neutrino problem

SNO results





2015 Nobel Prize

A. McDonald (SNO)

Neutrino oscillation understood

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)} \right)$$

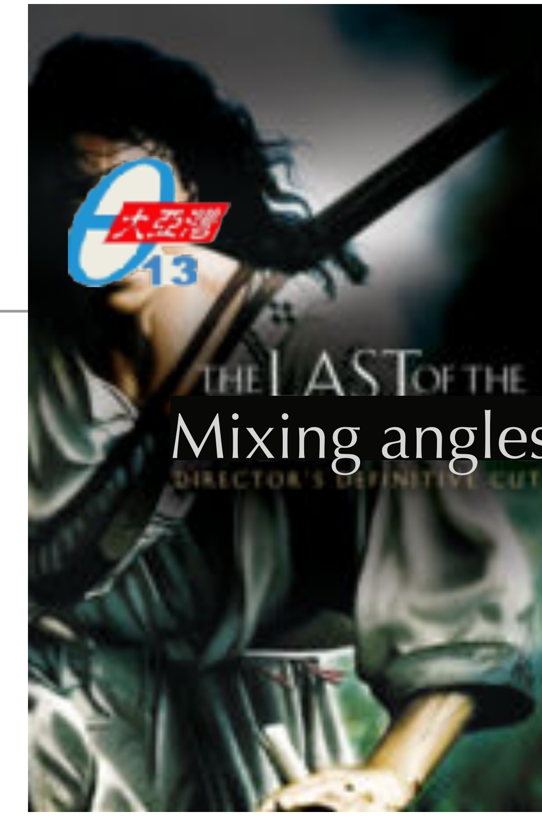
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{V} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

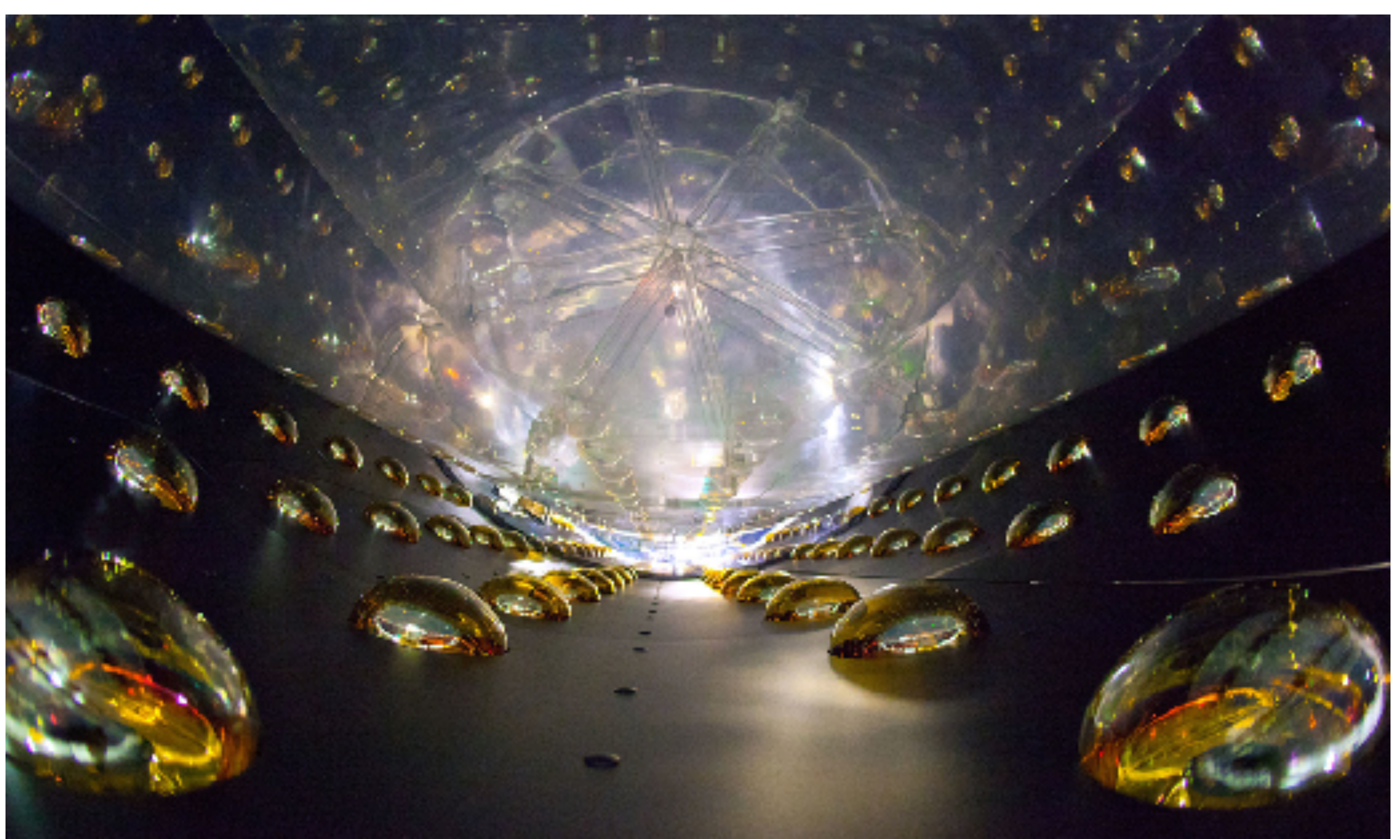
where

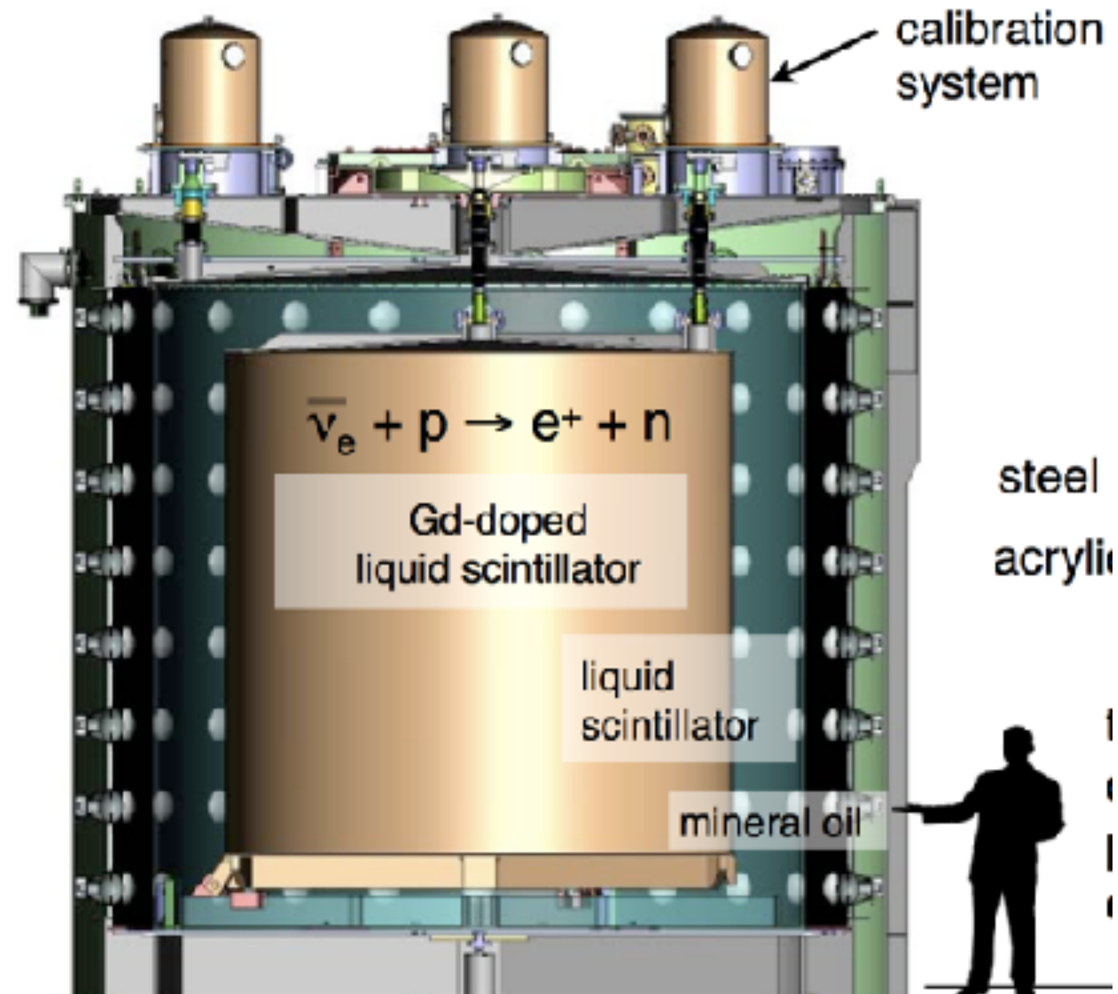
$$\mathrm{V} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

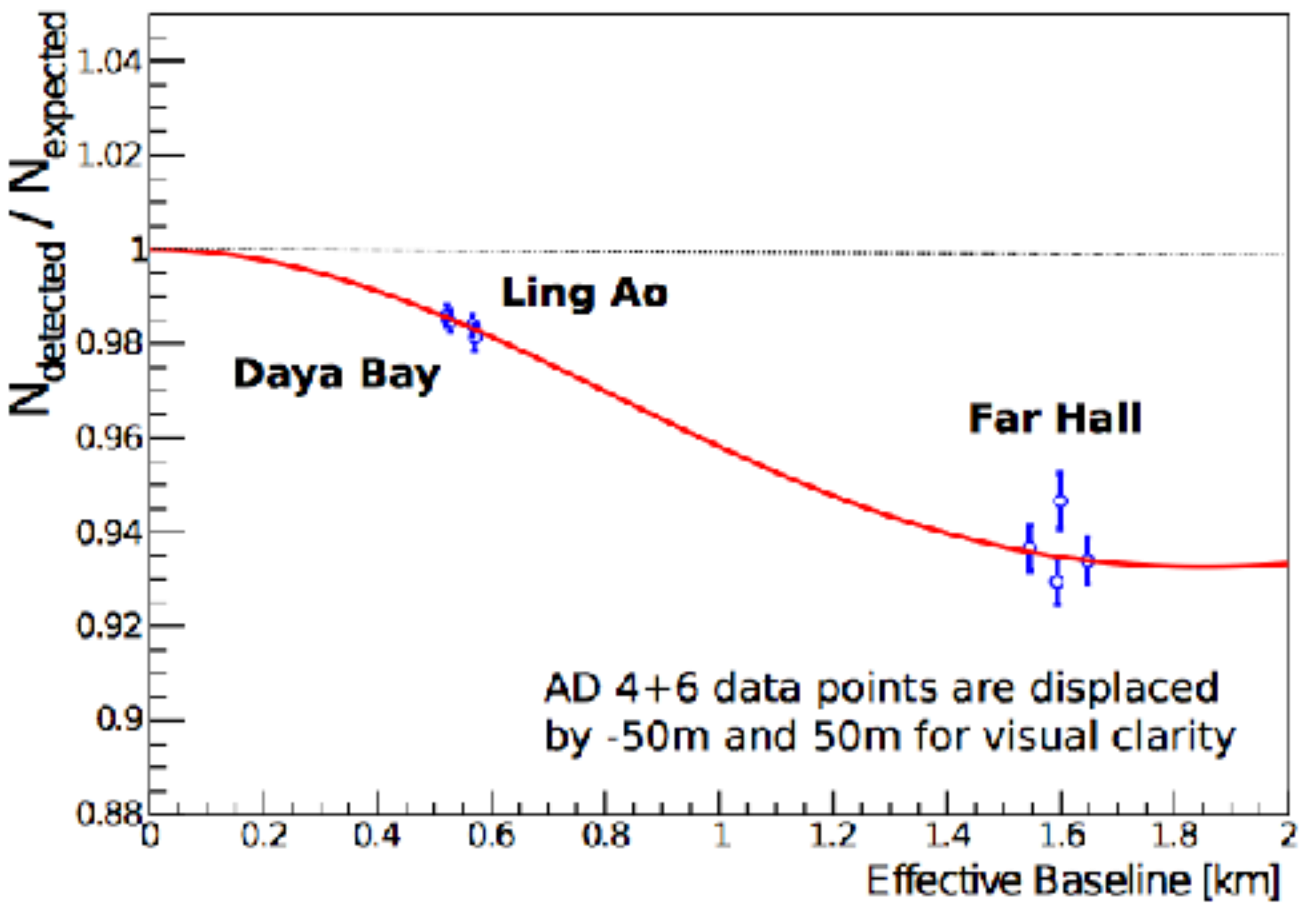
Daya-Bay and the Last of the angles

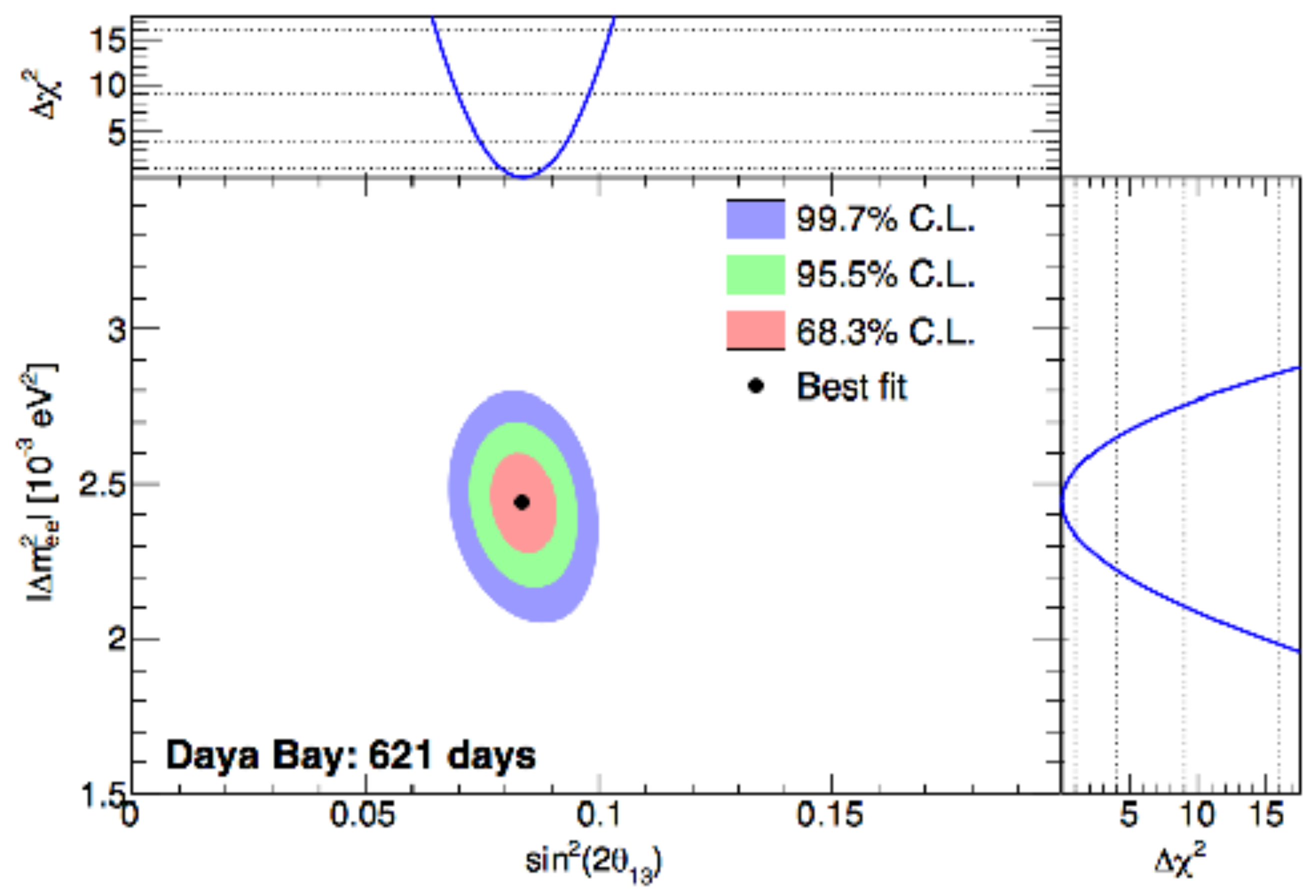






Daya-Bay and the Last of the angles





Neutrino oscillation understood

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)} \right)$$

$$\Delta m^2_{21}\ [10^{-5}\ \mathrm{eV}^{\ 2}] \quad 7.54^{+0.26}_{-0.22}$$

$$|\Delta m^2|\ [10^{-3}\ \mathrm{eV}^{\ 2}] \quad 2.43 \pm 0.06$$

$$\sin^2\theta_{12} \quad 0.308 \pm 0.017$$

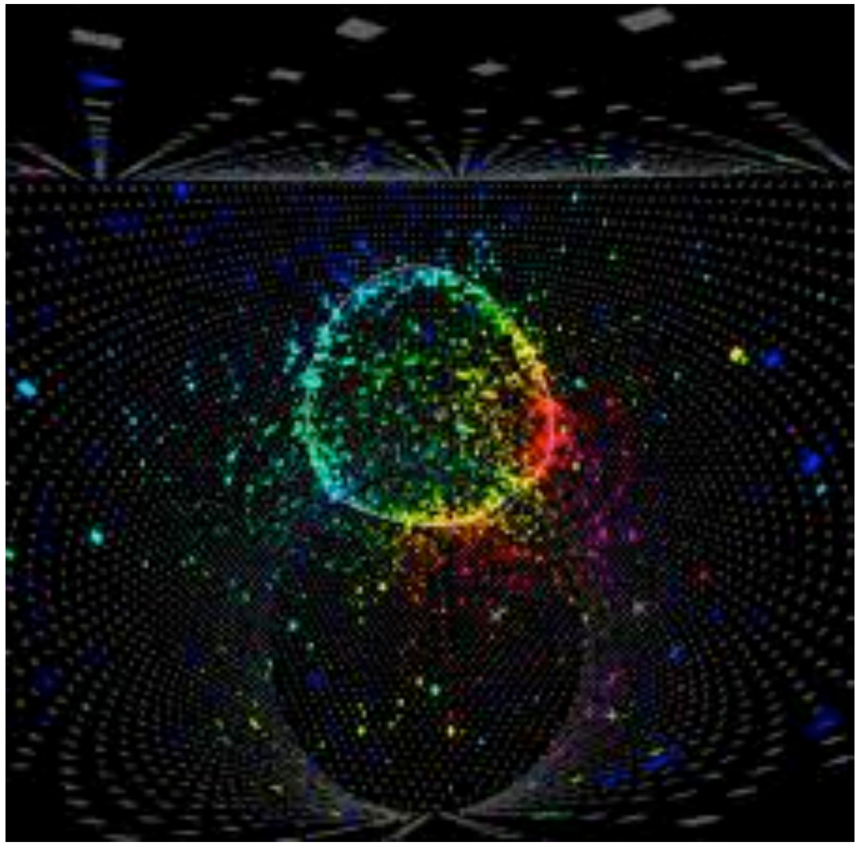
$$\sin^2\theta_{23} \quad 0.437^{+0.033}_{-0.023}$$

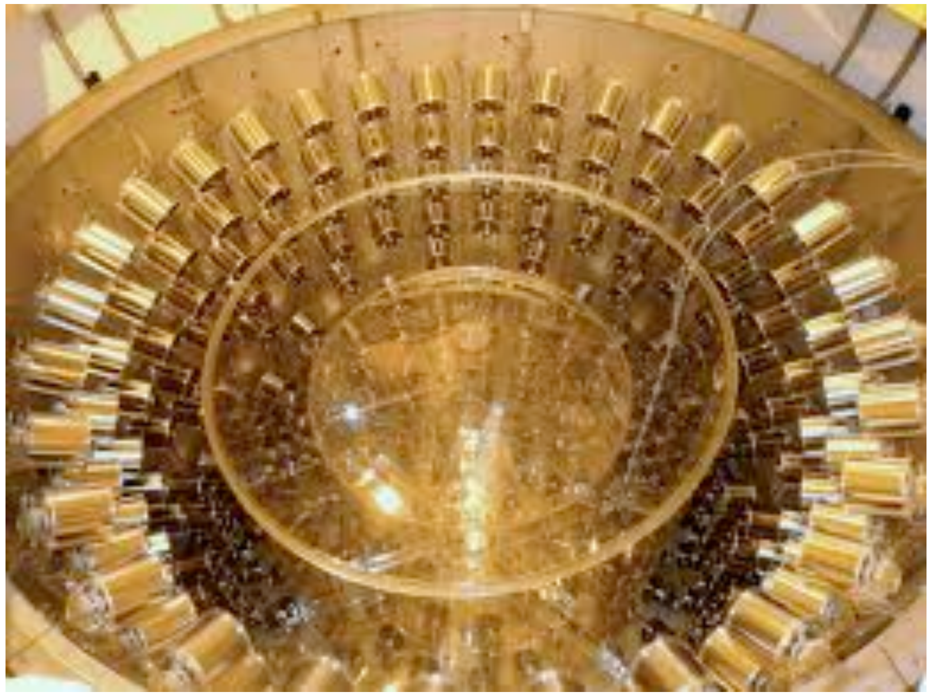
$$\sin^2\theta_{13} \quad 0.0234^{+0.0020}_{-0.0019}$$

Paradigm shift

- Until the discovery of neutrino oscillation (1998), neutrinos were not considered a priority in Particle Physics
- Oscillation (hence mass) radically changed the perspective on neutrinos
- The measurement of θ_{13} (2011), the last mixing angle, was the last missing element for neutrino physicists to go full-steam ahead with large scale neutrino experiments
- Remaining questions (mass ordering, CP-violation) are now accessible

Neutrino detection

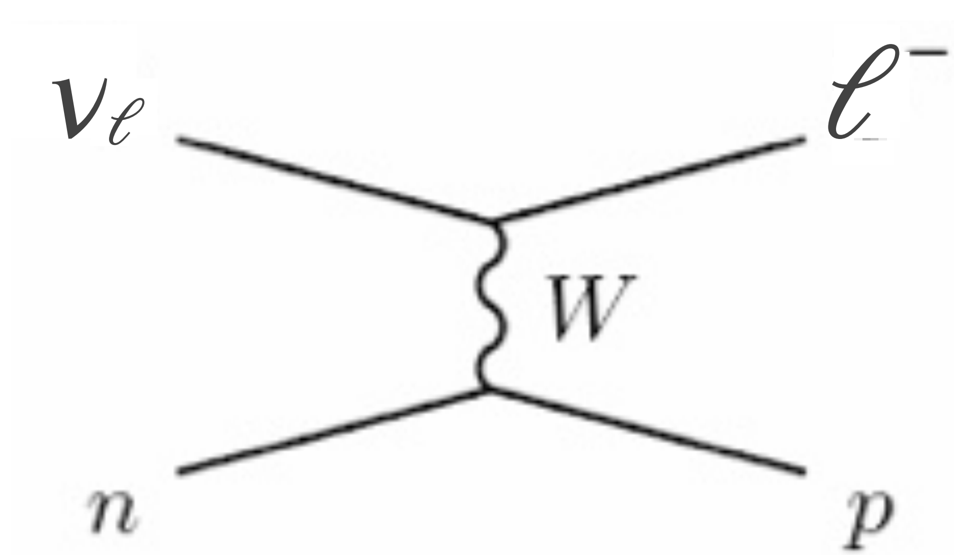




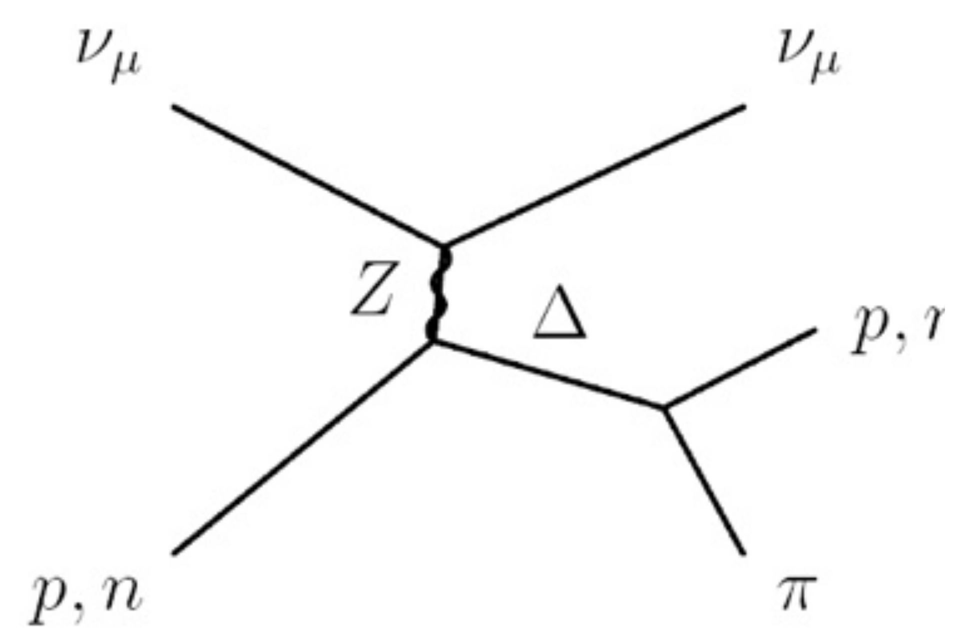
Neutrino detection

- Neutrinos are not detected directly
- Neutrinos interact via “Charged” or “Neutral” currents
- Products of the interactions are detected

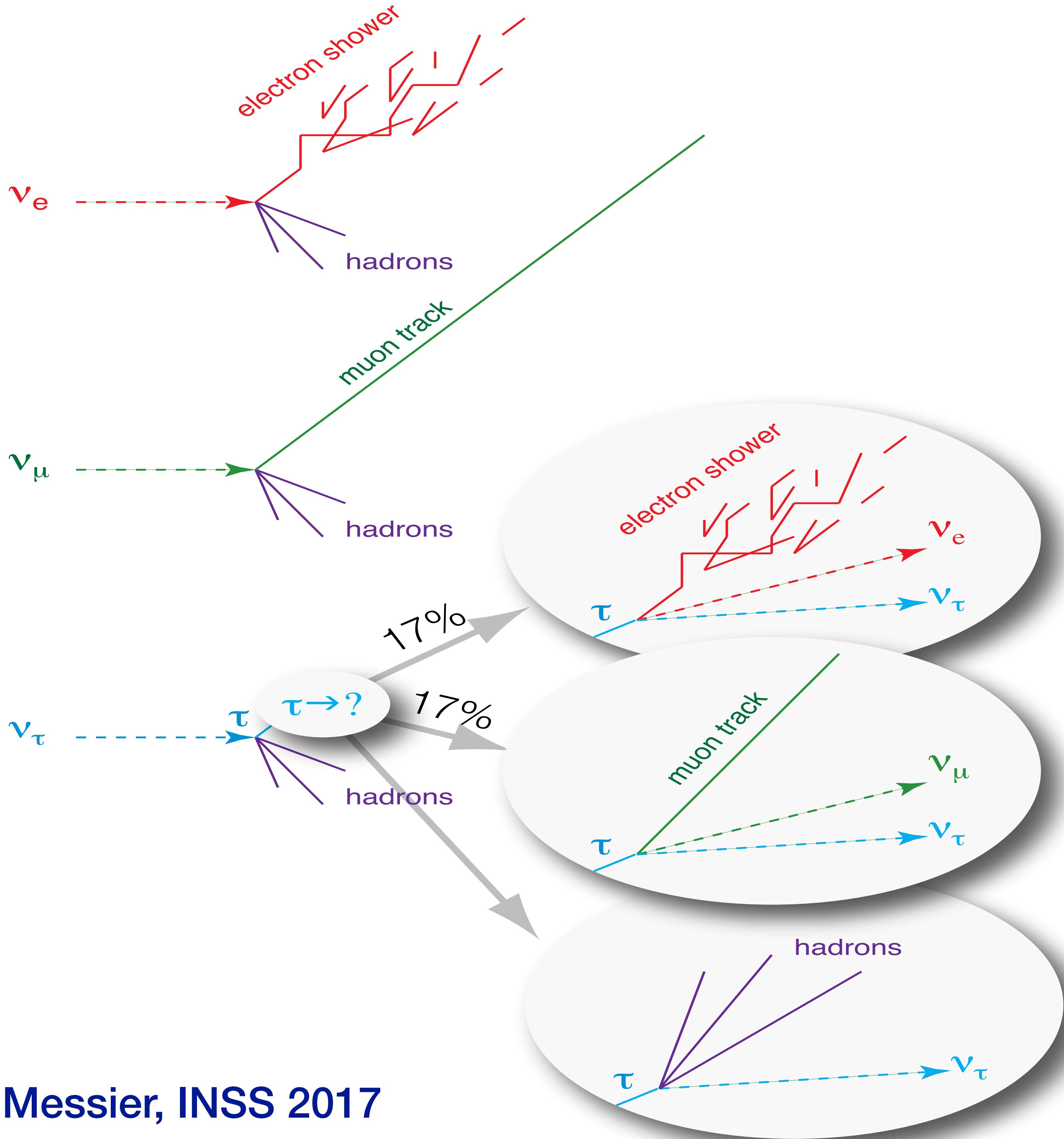
Charge Current (CC) Interactions



Neutral Current (NC) Interactions

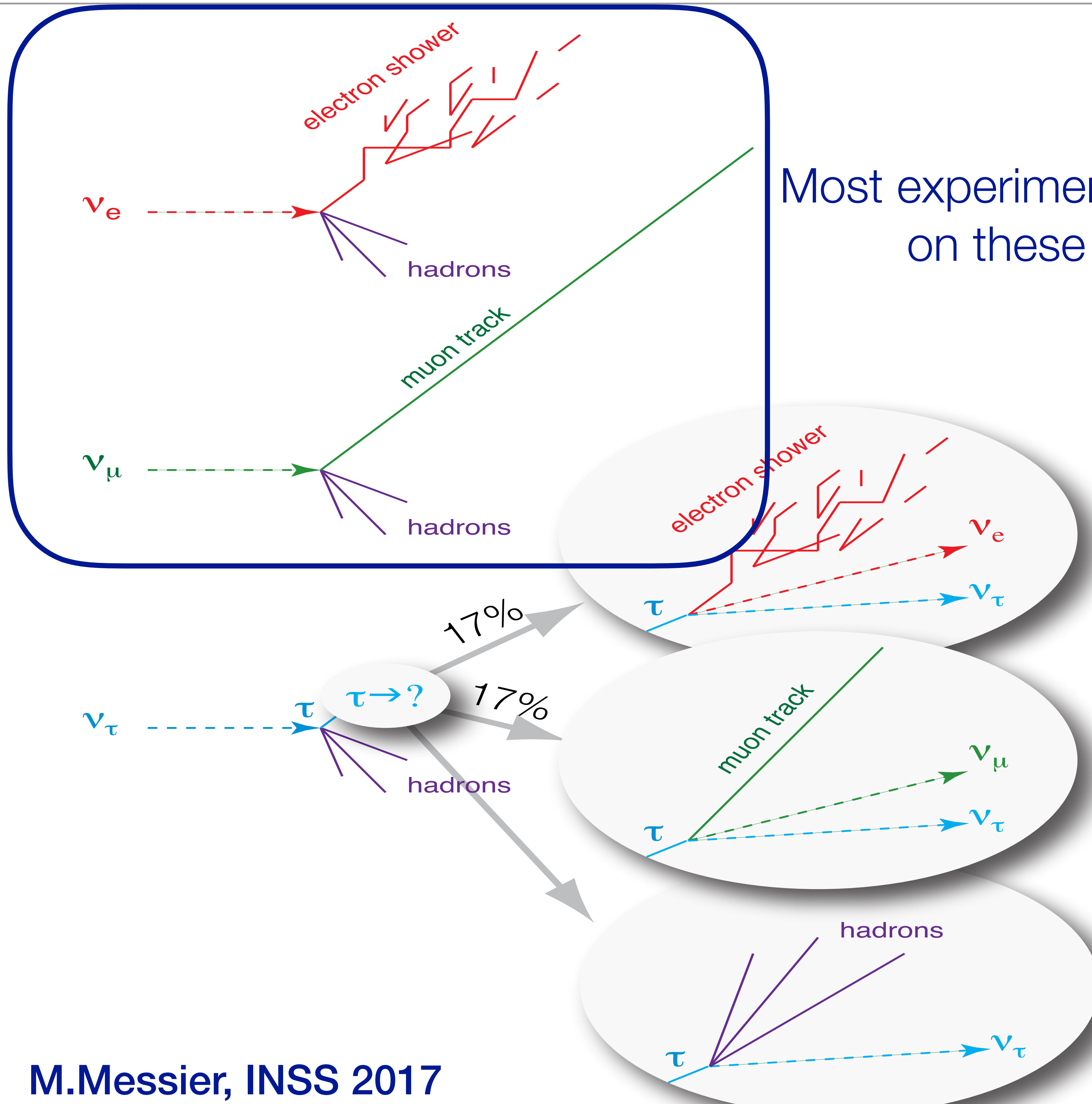


Neutrino detection



M.Messier, INSS 2017

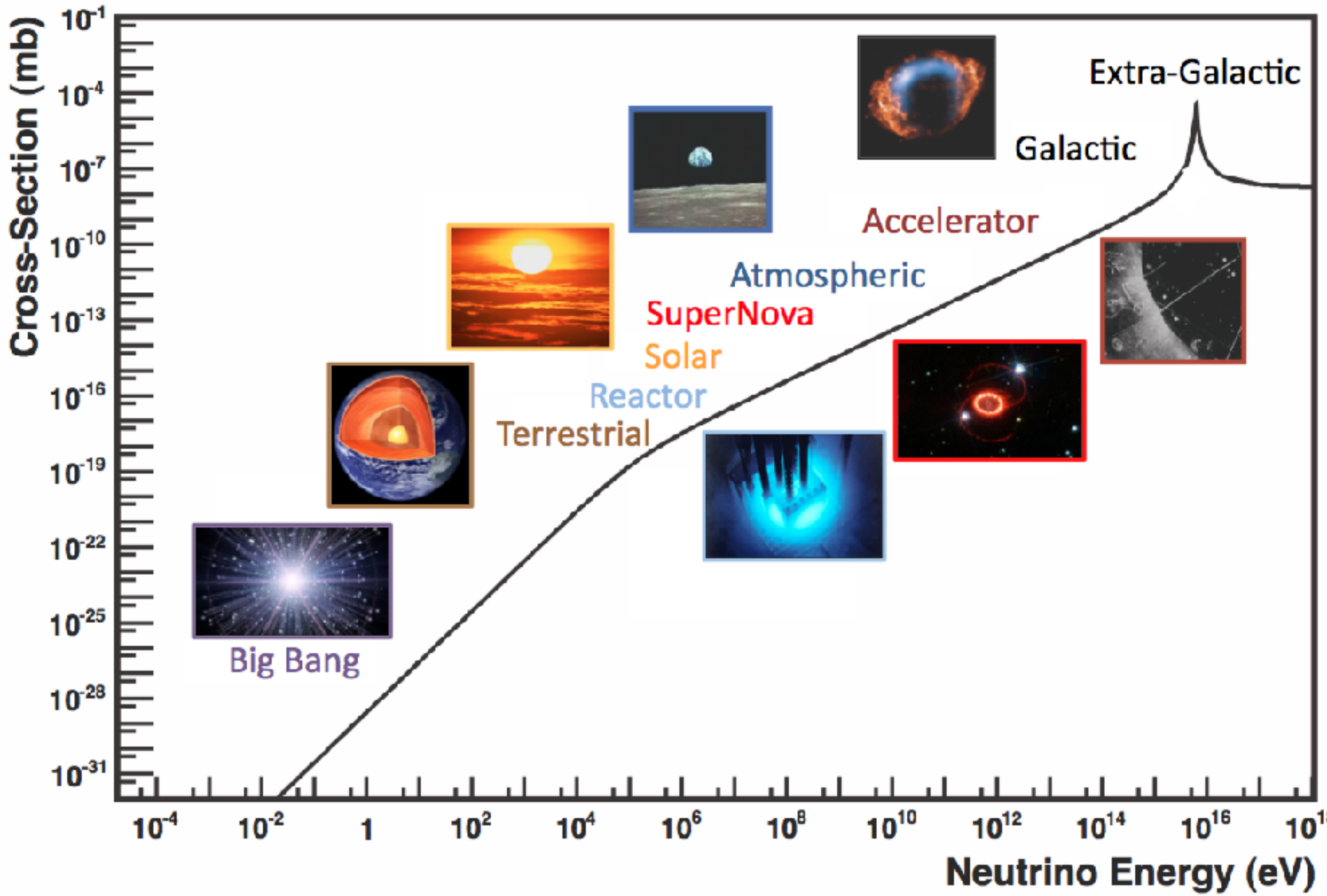
Neutrino detection



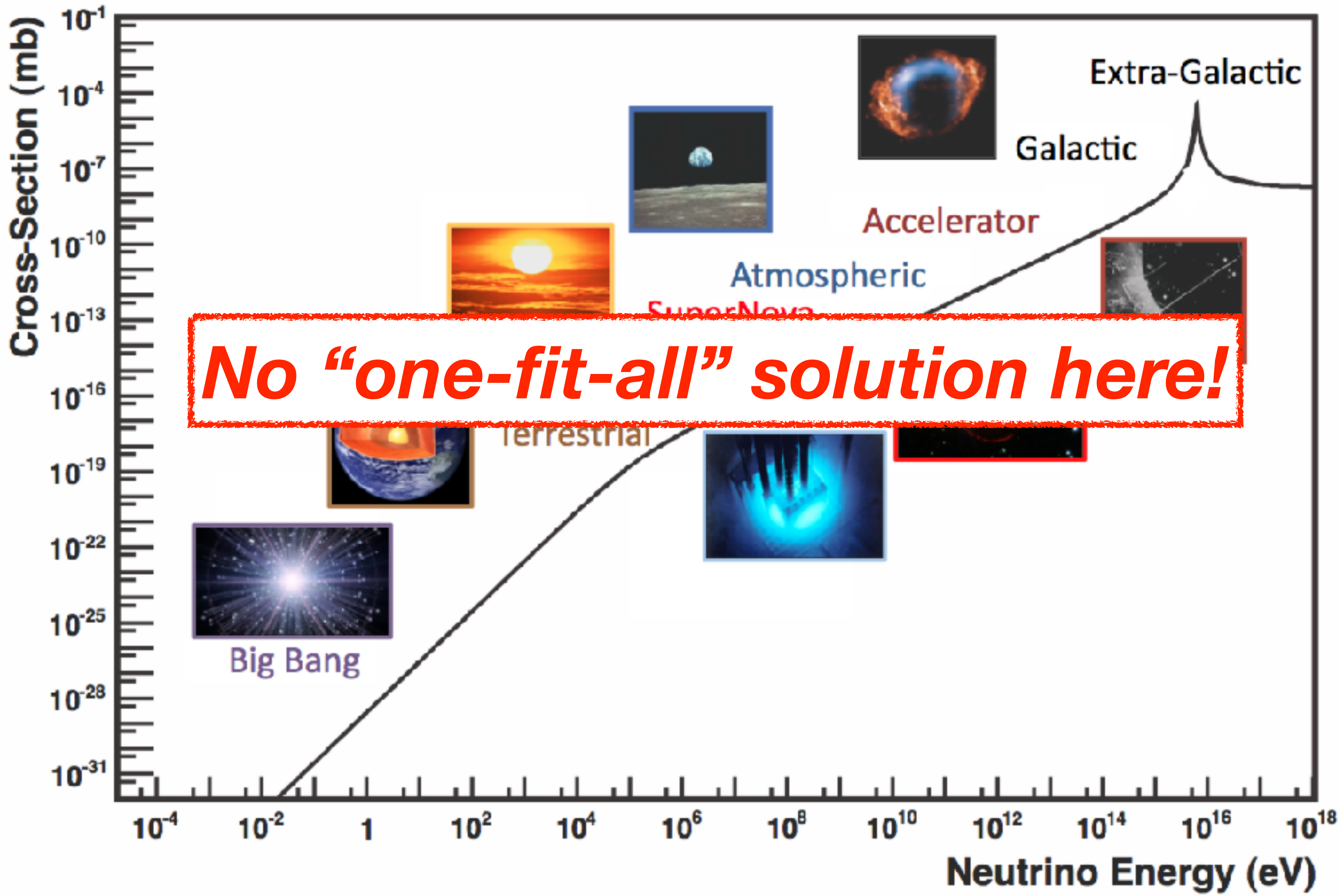
Most experiments concentrate on these channels

M.Messier, INSS 2017

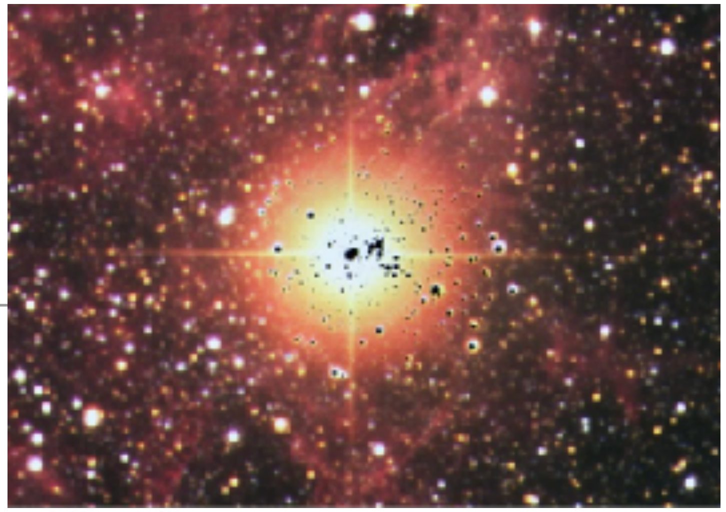
Neutrino sources, energies and cross-section

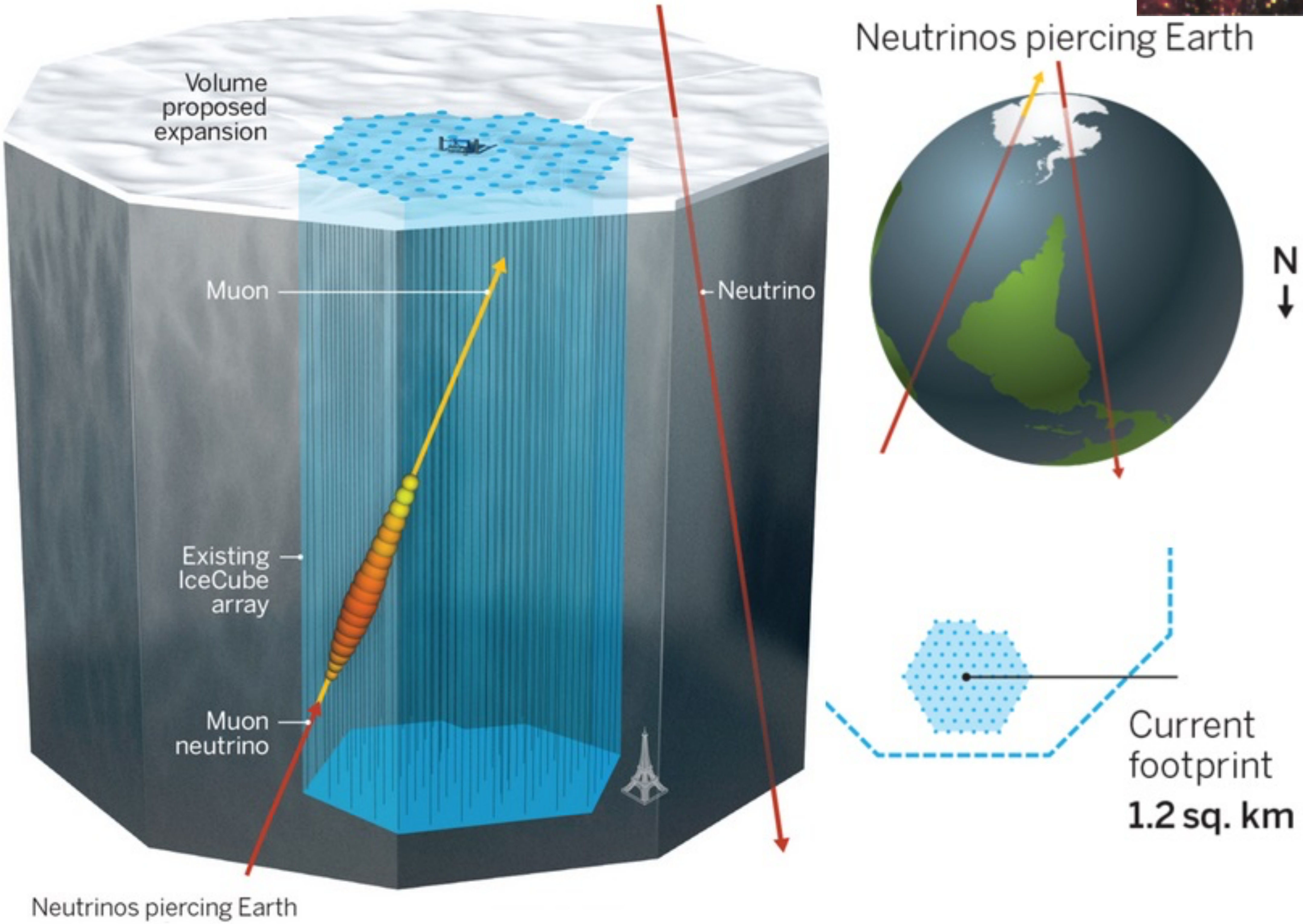


Neutrino sources, energies and cross-section

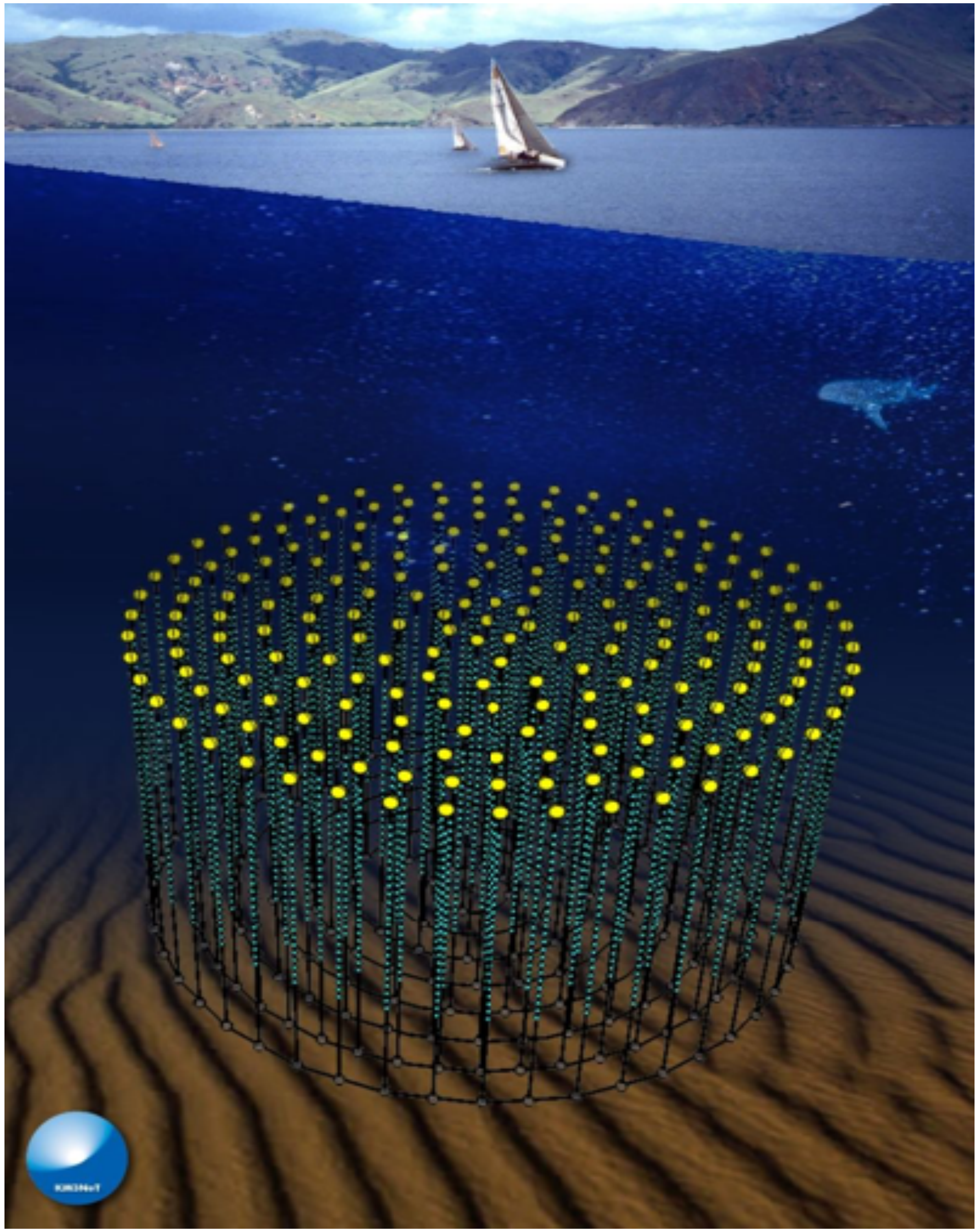


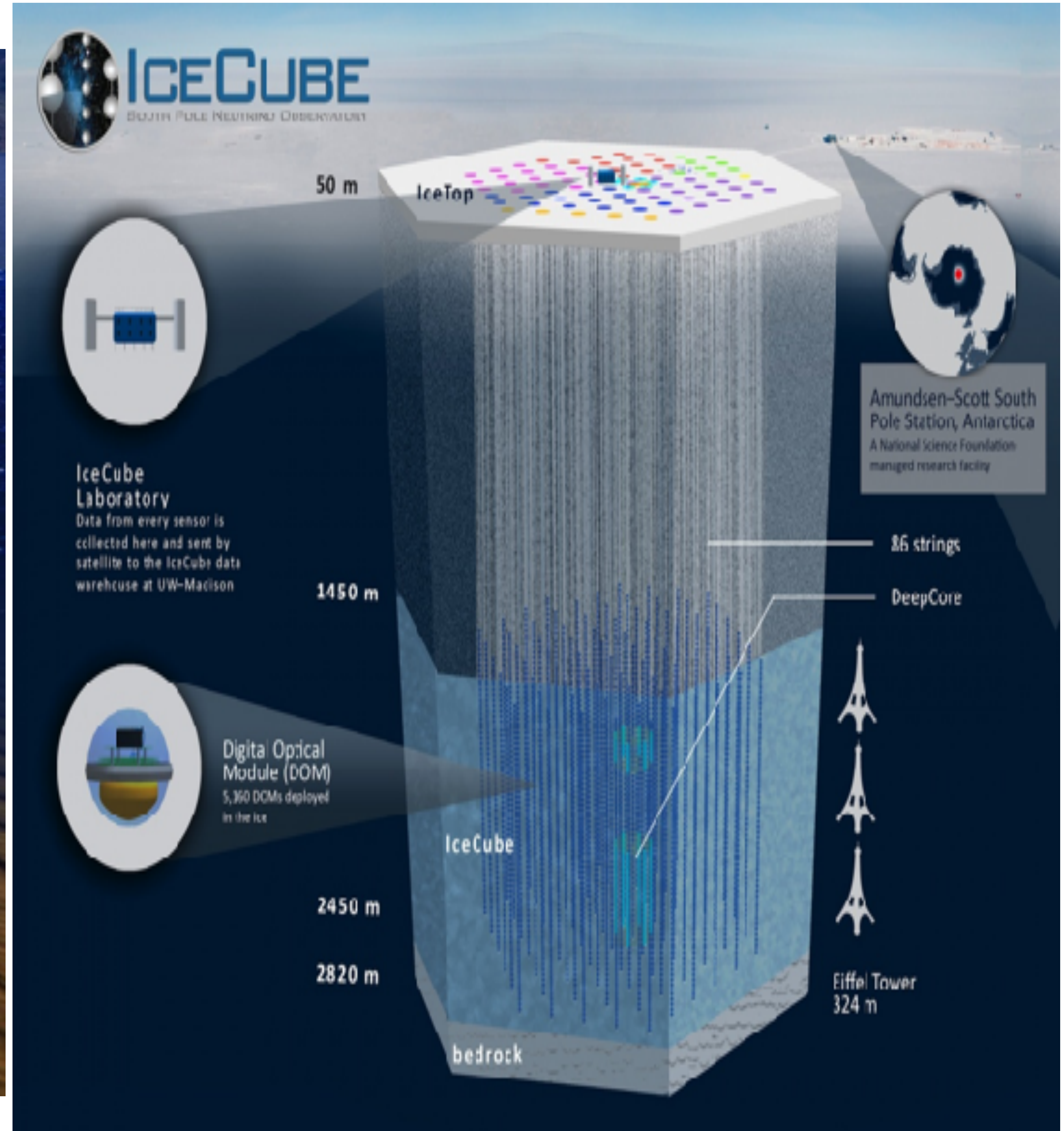
Very-high-Energy (TeV to PeV)





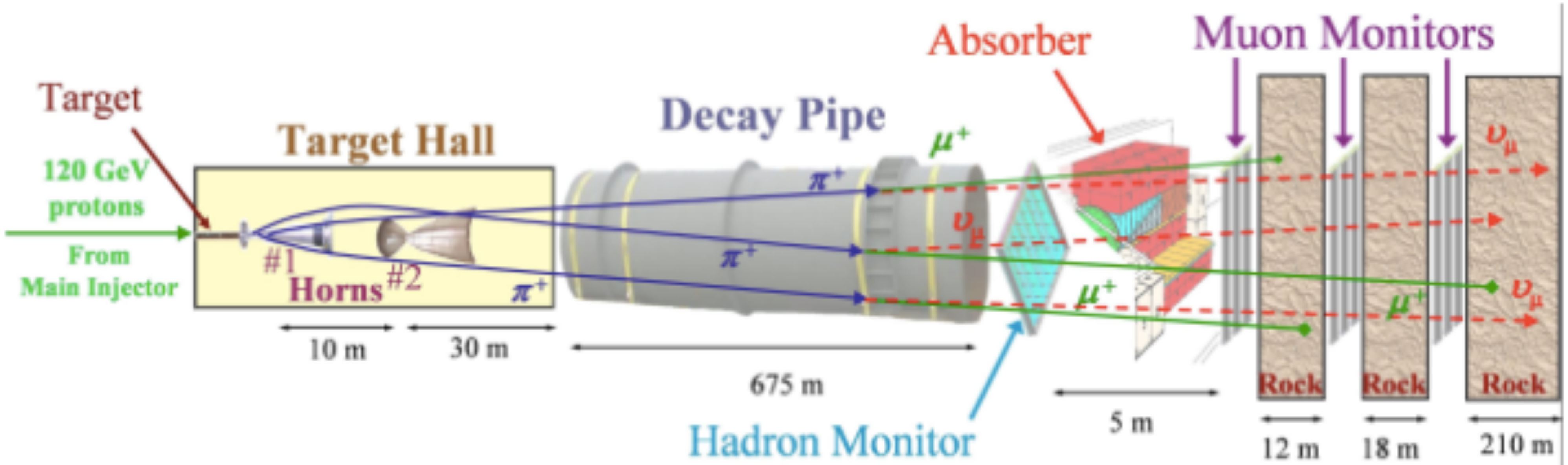
Very-high-Energy (TeV to PeV)

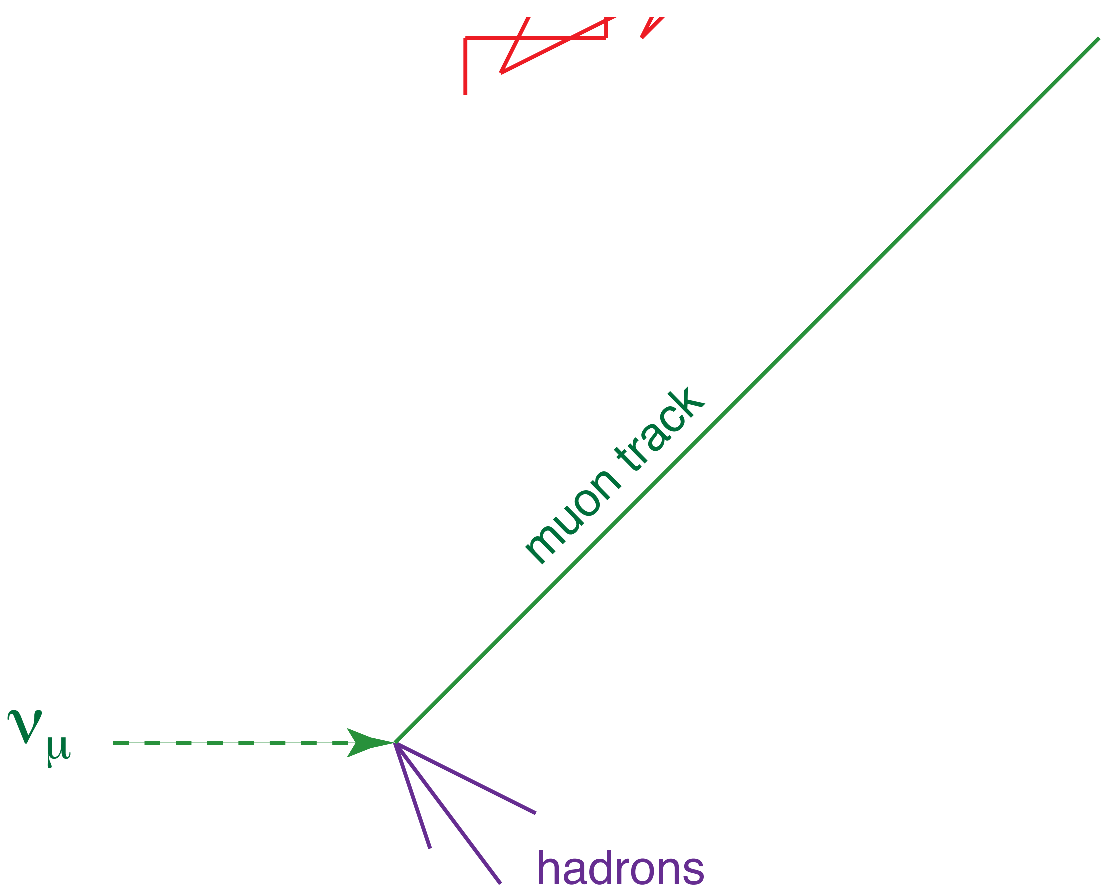


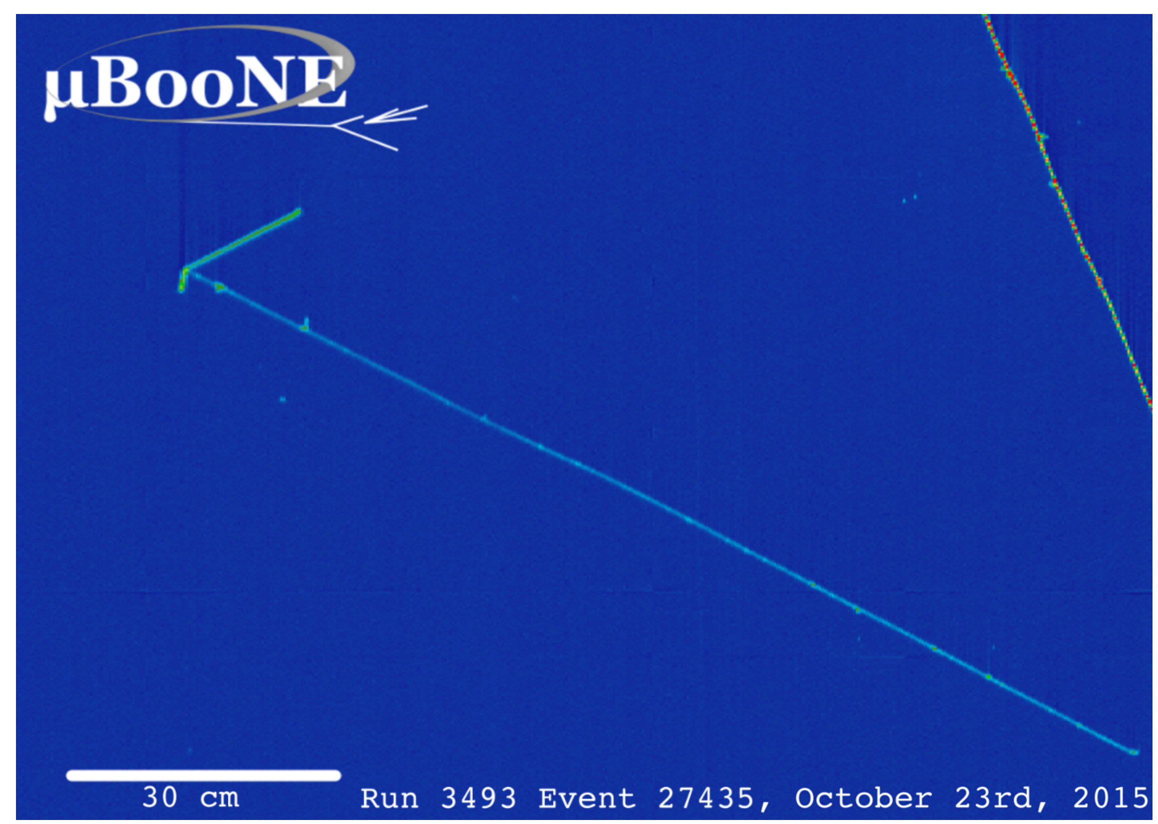


High Energy (MeV to GeV)

- Mainly human-made (accelerator)

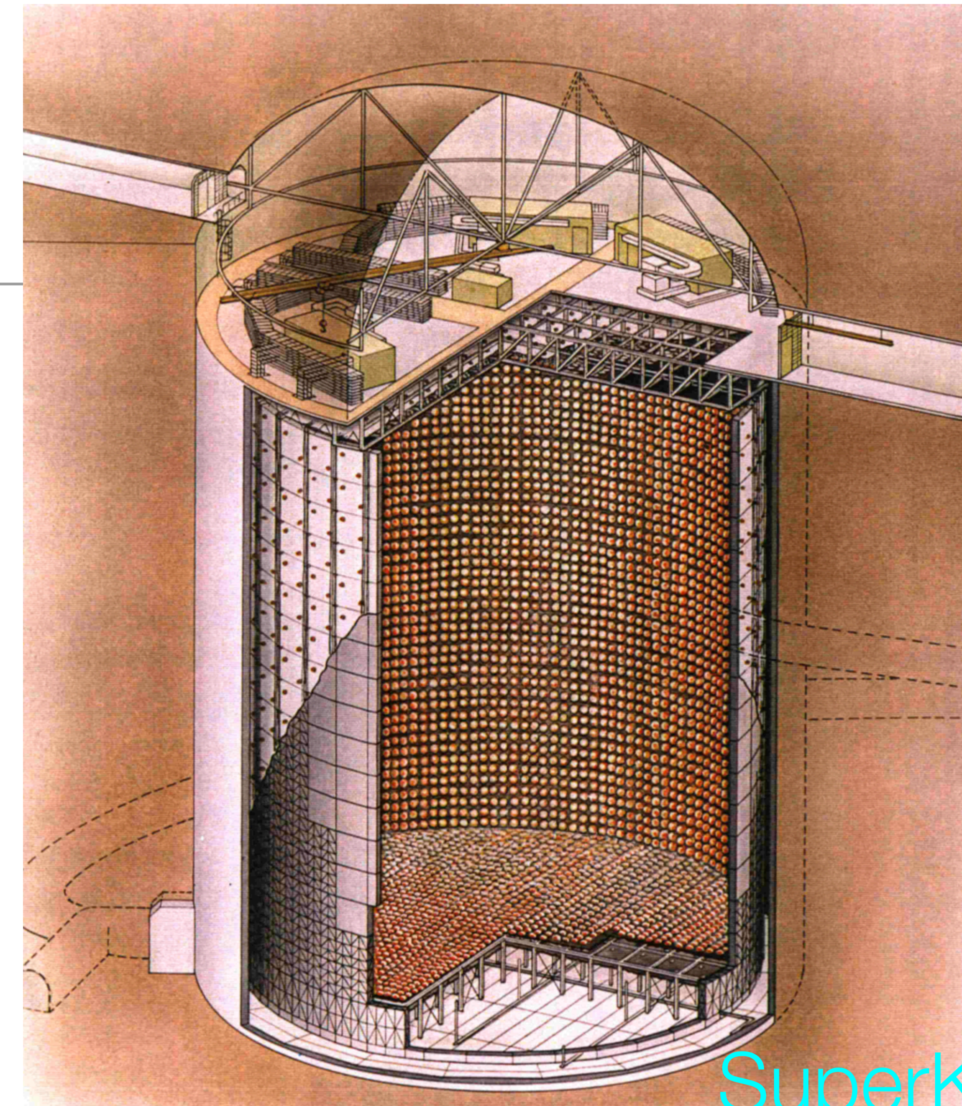


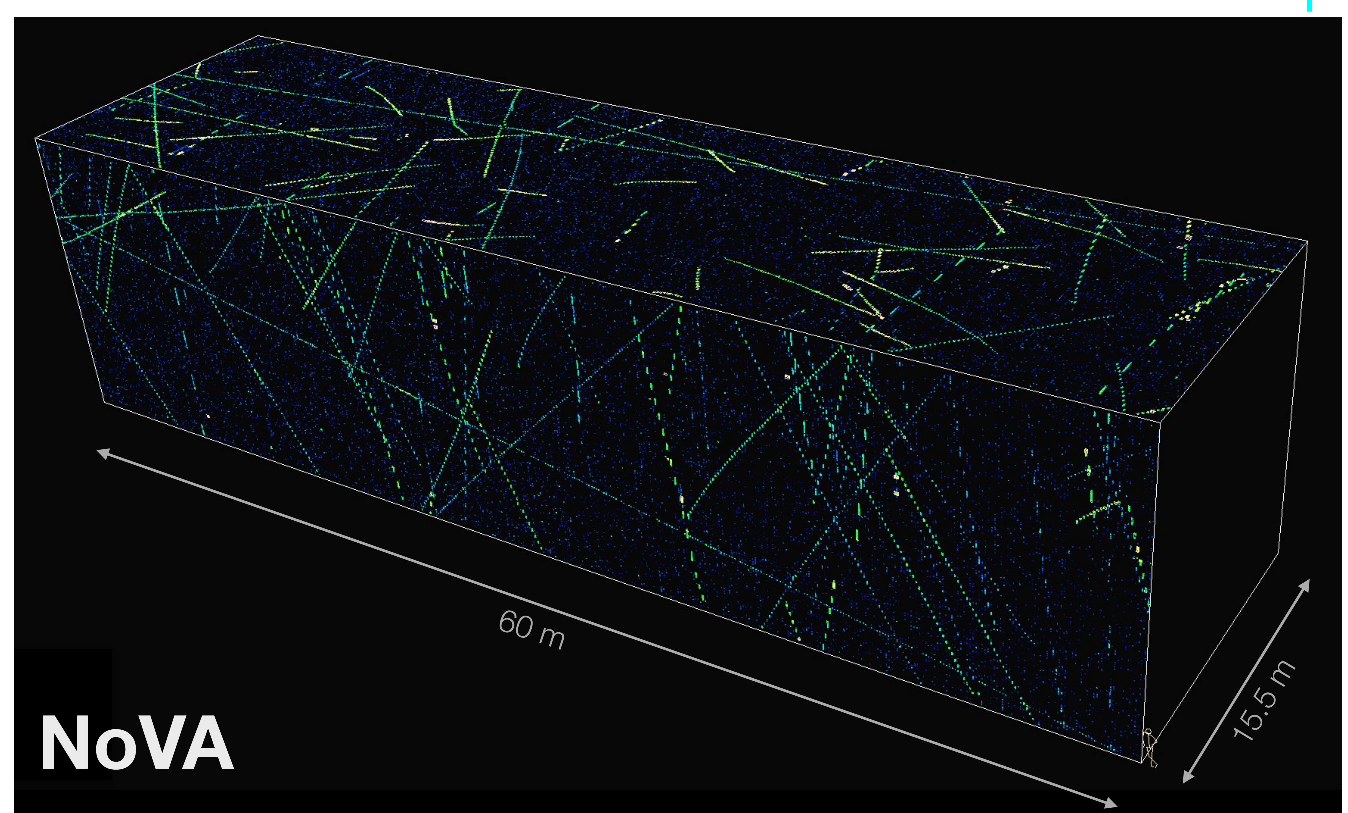




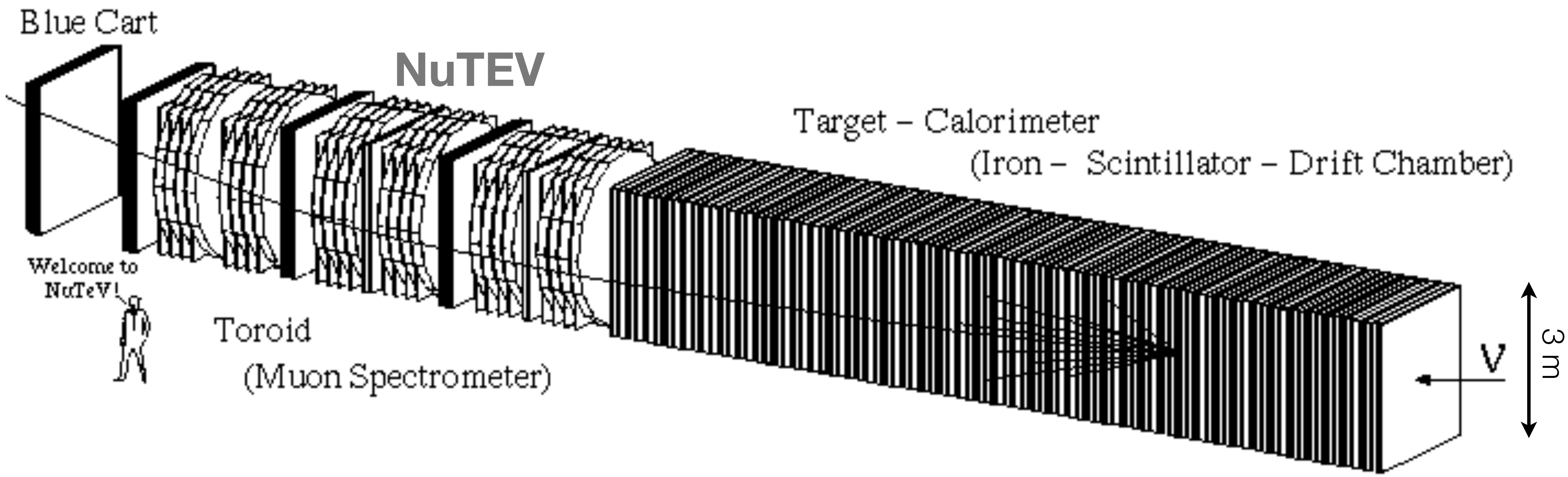
High Energy (MeV to GeV)

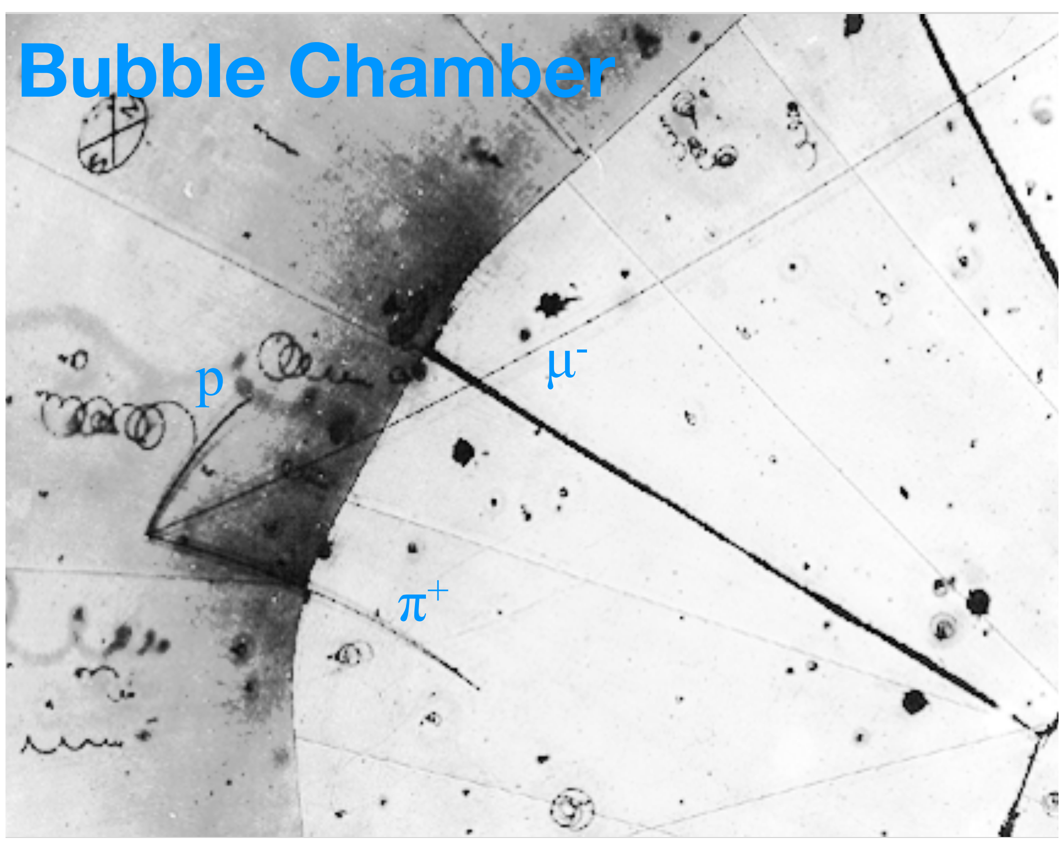
Large variety of detectors
in this energy range



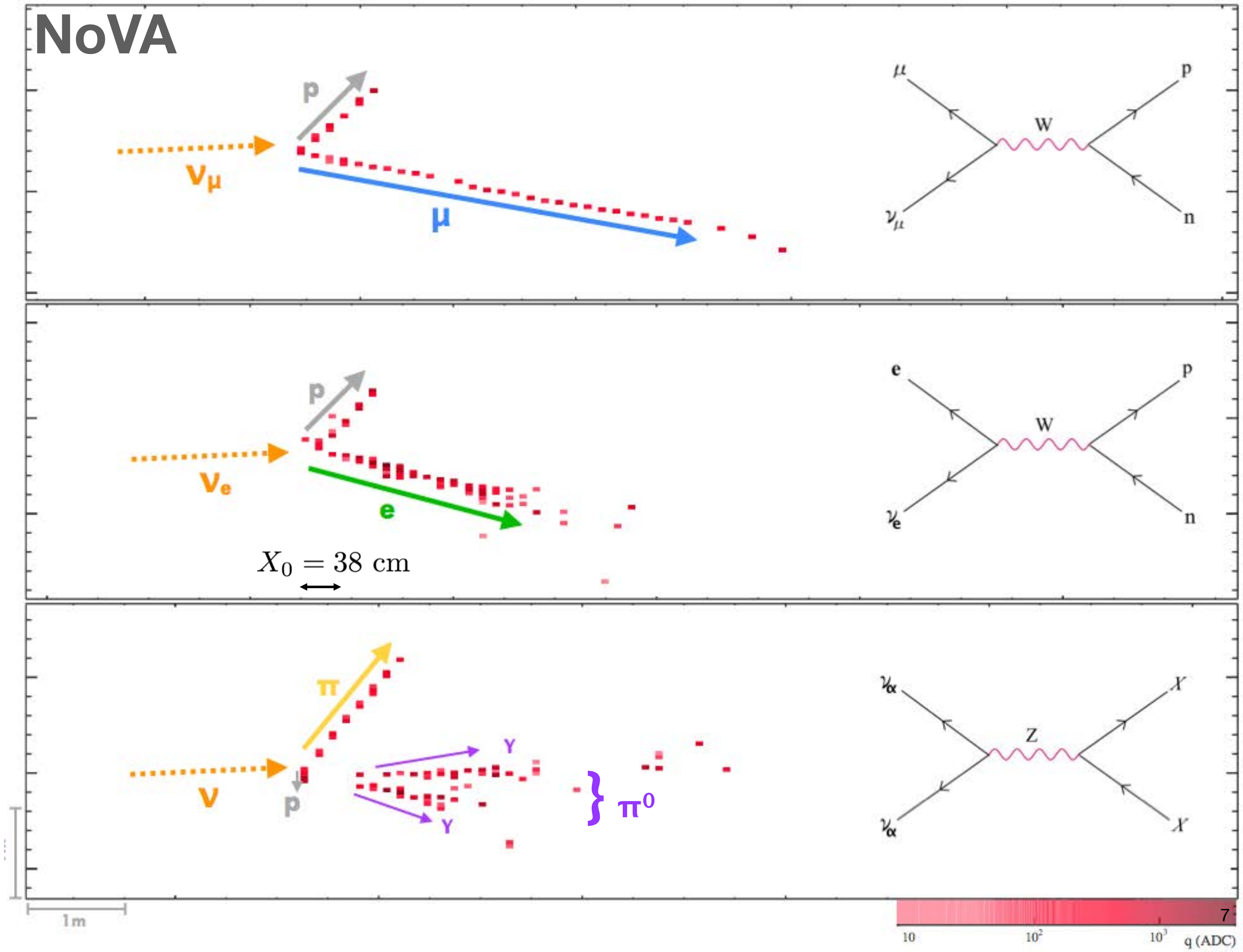


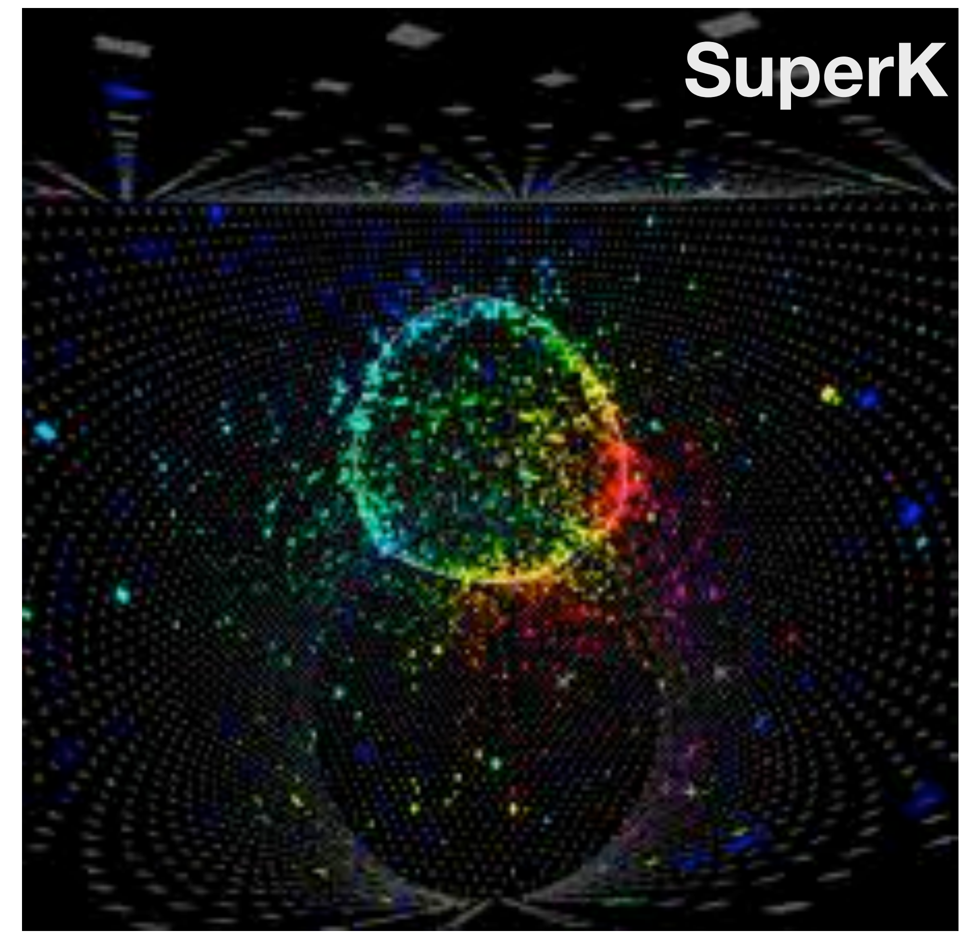
High Energy (MeV to GeV)





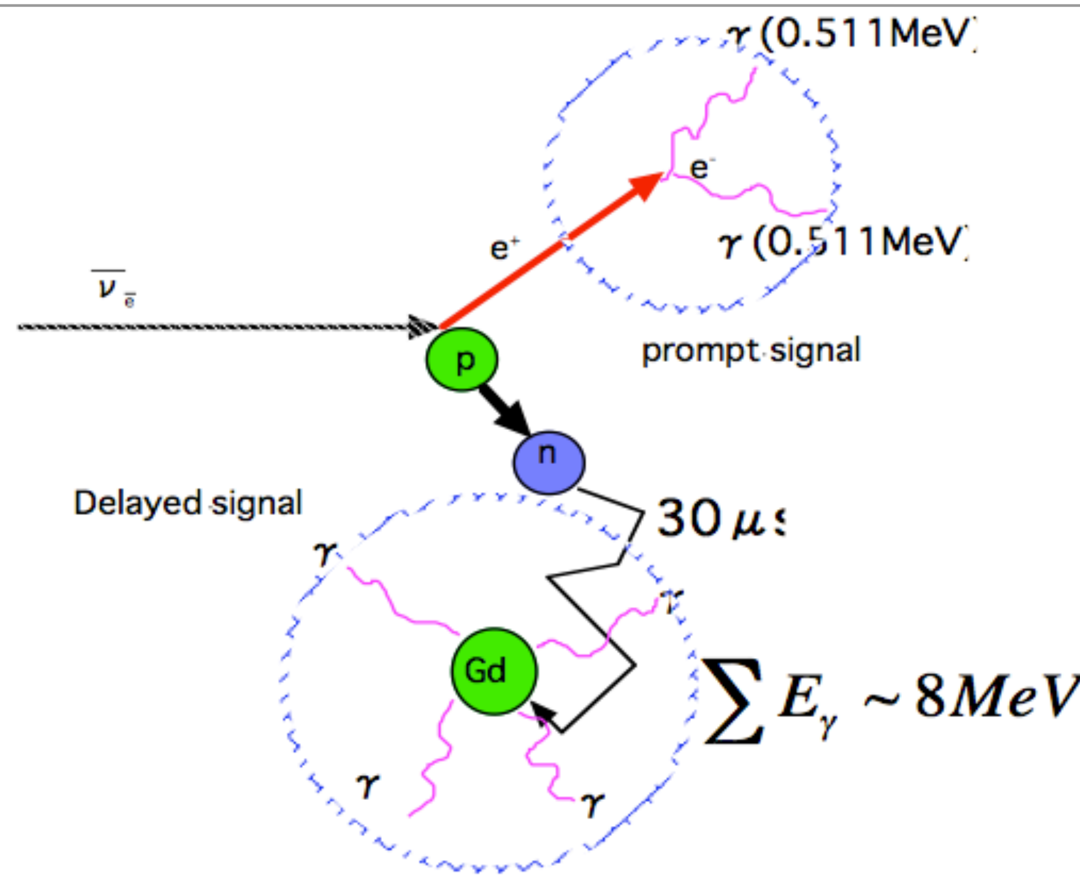
High Energy (MeV to GeV)

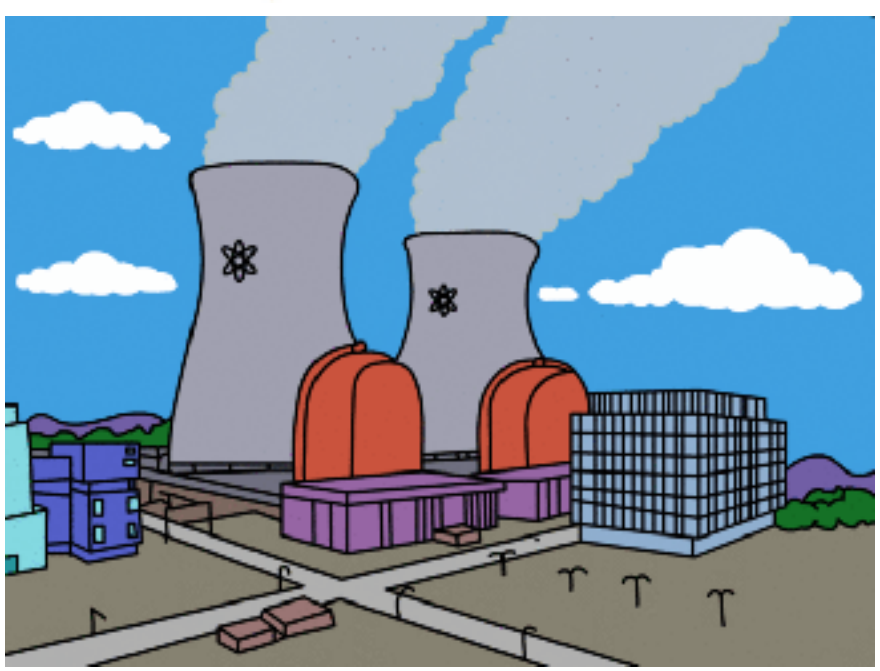


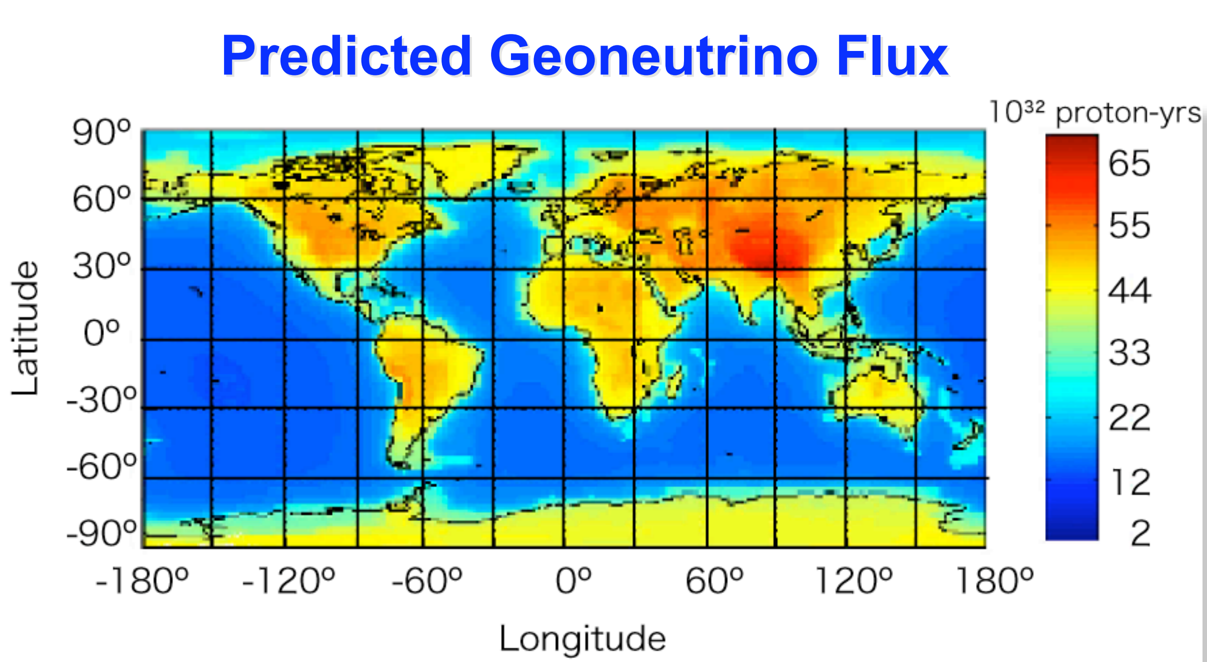


Low-energy detectors (~1 - 100 MeV)

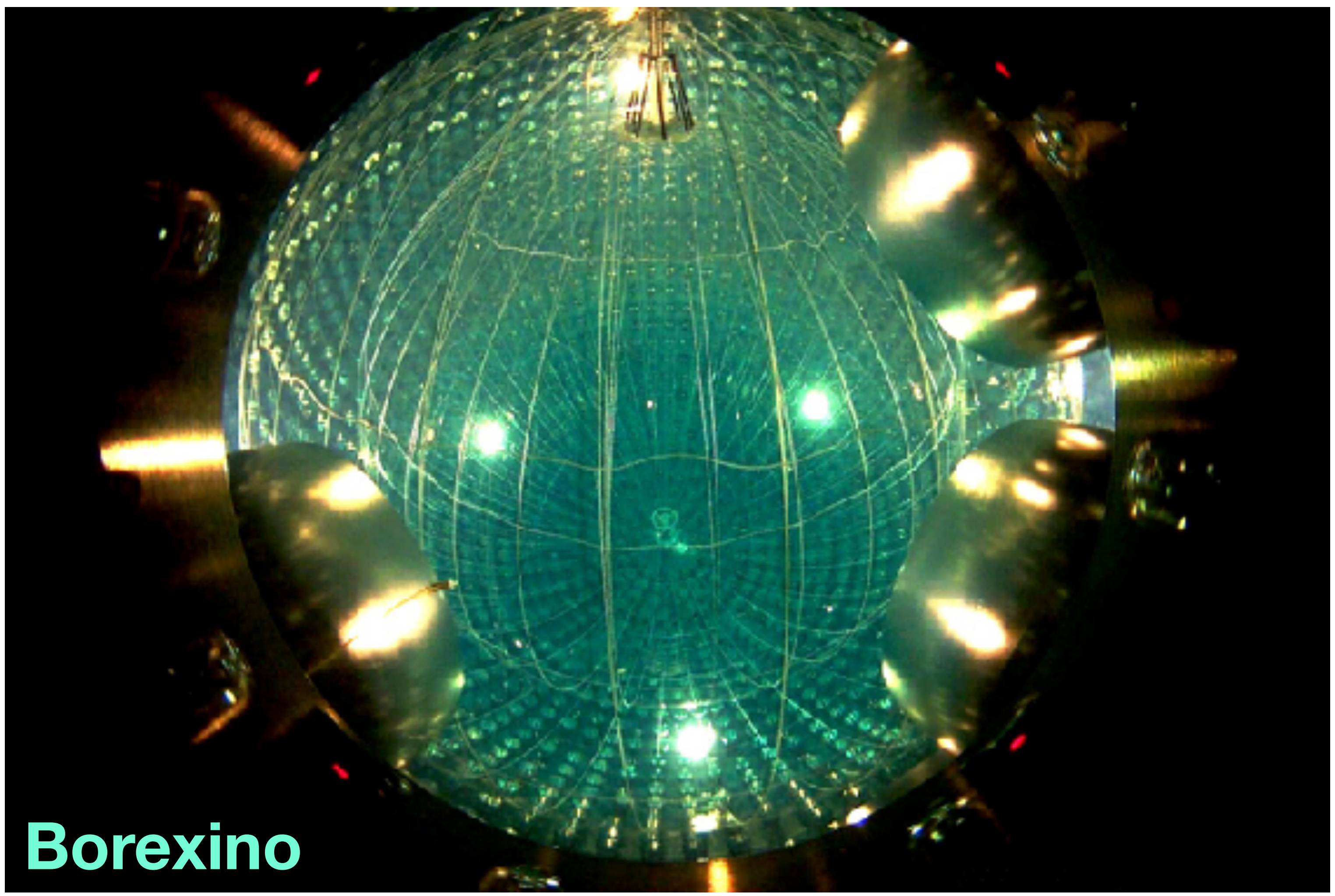
In this energy range only liquid scintillator using inverse beta decay can efficiently detect neutrinos

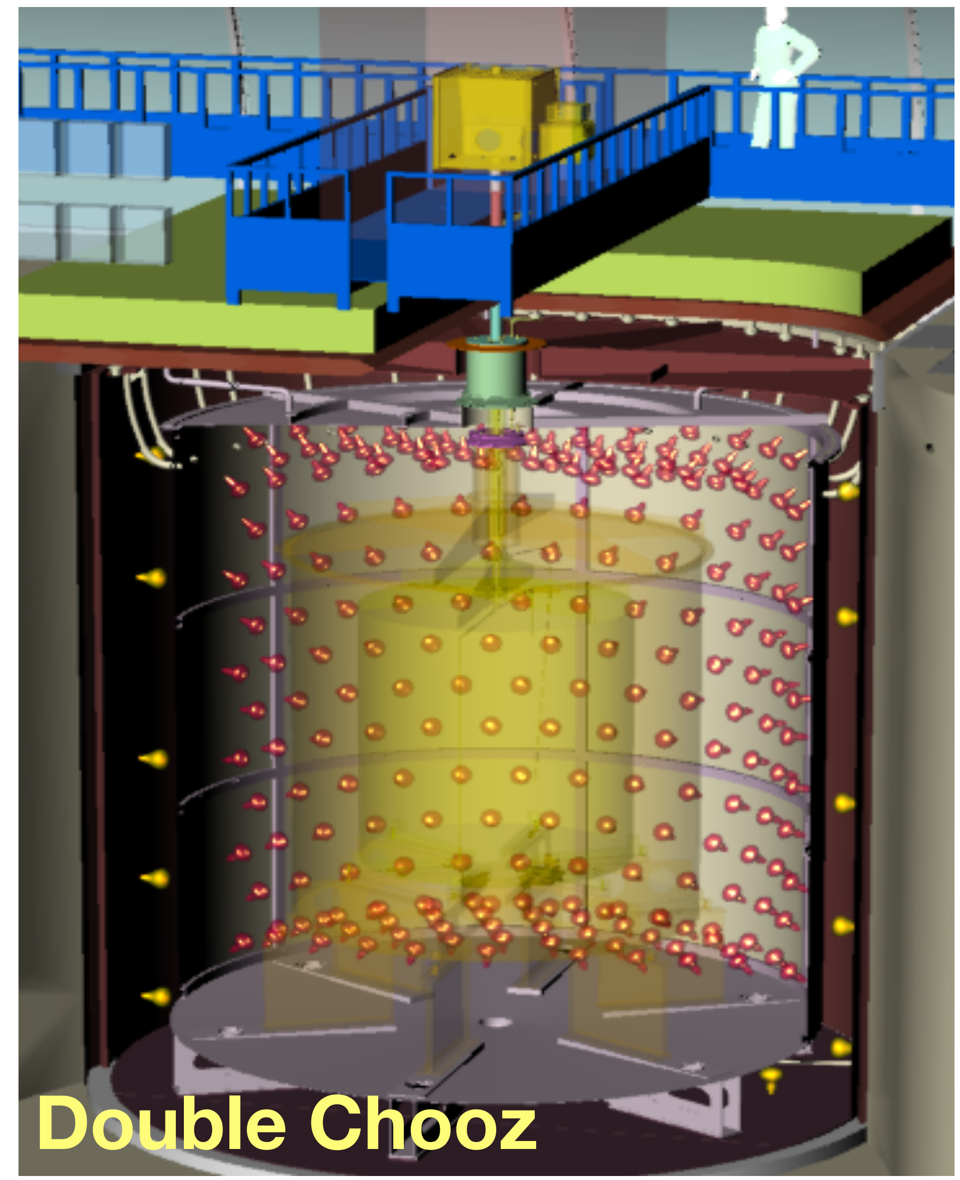






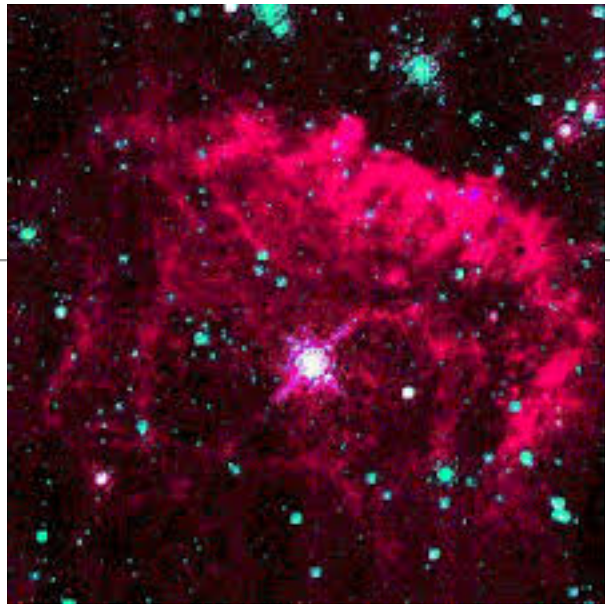
Low-energy detectors





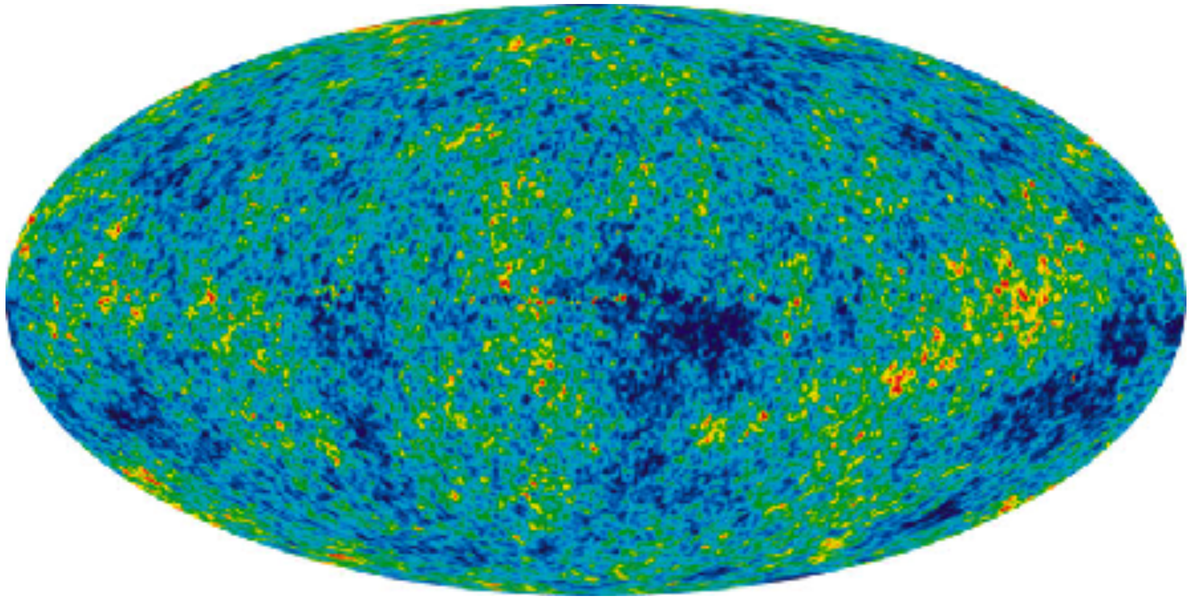
Even lower energy…

- From all the supernovae that have ever exploded, a significant fraction of neutrinos are still wandering in the Universe

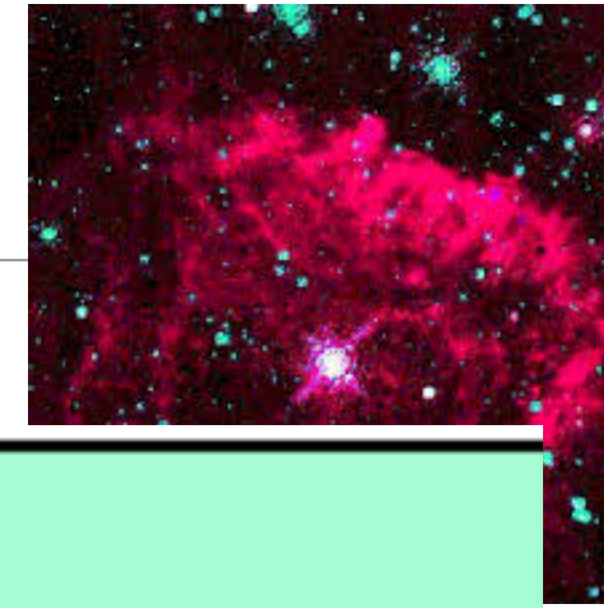


- Cosmic Neutrino Background (CNB)
- ~300/cm^3

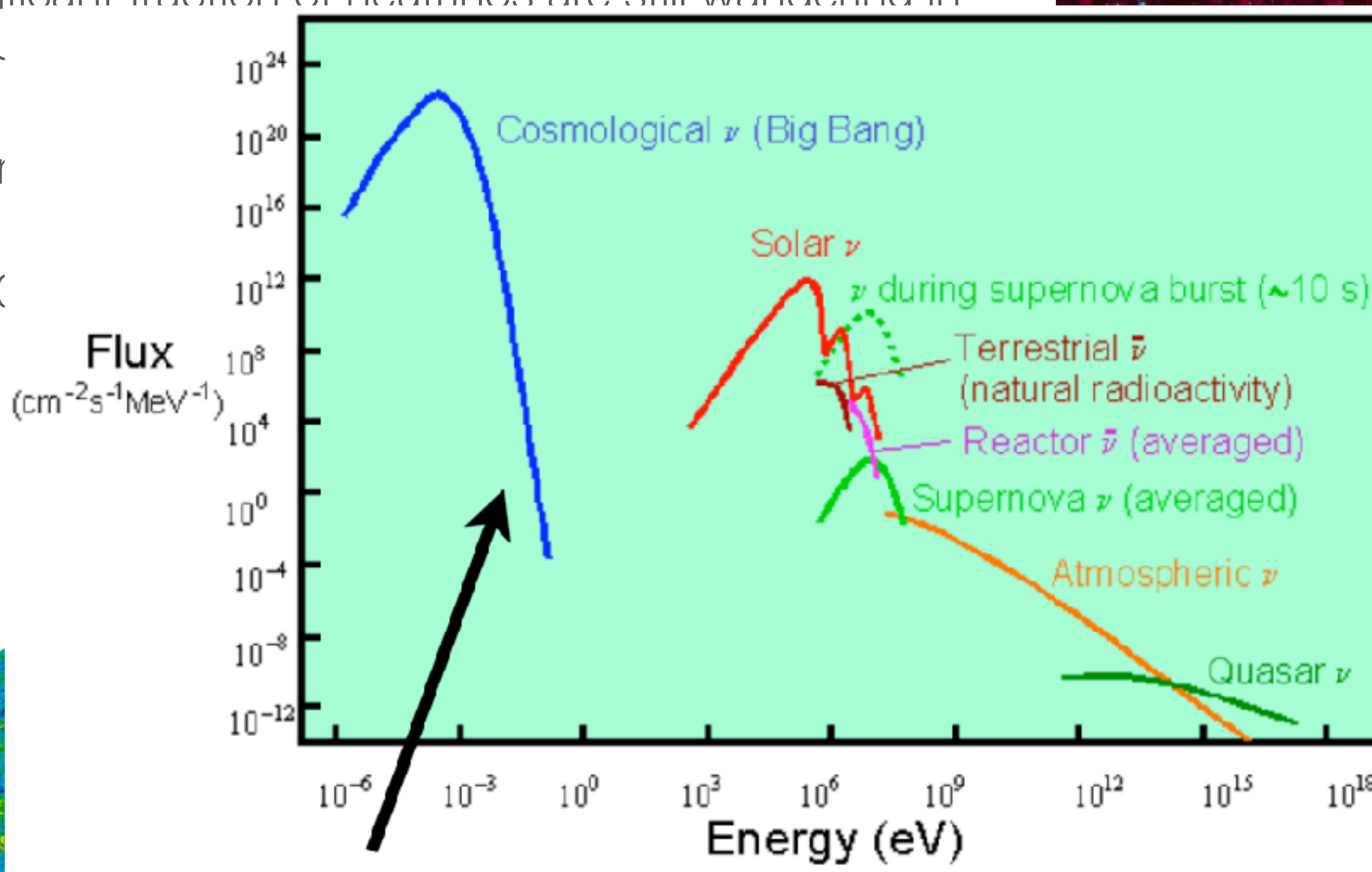
The dream…

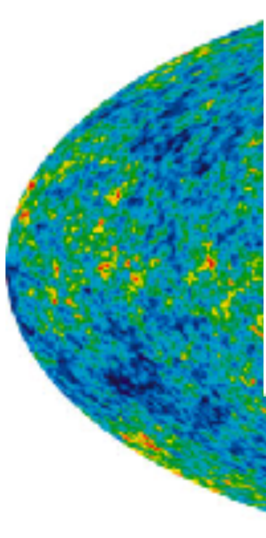


Even lower energy…



- From all the supernovae that have ever exploded, a significant fraction of neutrinos are still wandering in the U
- Cos
- ~30





How do we go forward now?

- All previous experiments successfully achieved their goals and many made great discoveries!
- Neutrino physicists now have all the information to design the next generation of experiments to address some of the remaining great questions of neutrino physics

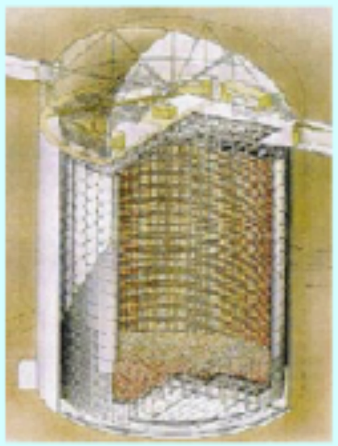
  ✓ What is the mass hierarchy (ordering)

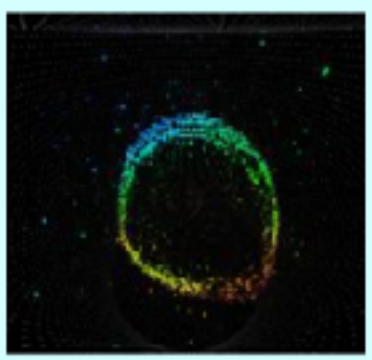
  ✓ Is there CP violation? What is δ_{CP}?

  ✓ Are there sterile neutrinos?

Main paths forward

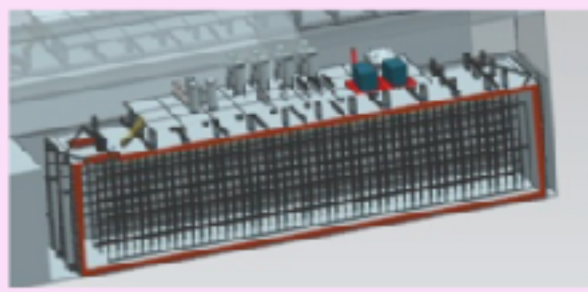
Water Cherenkov

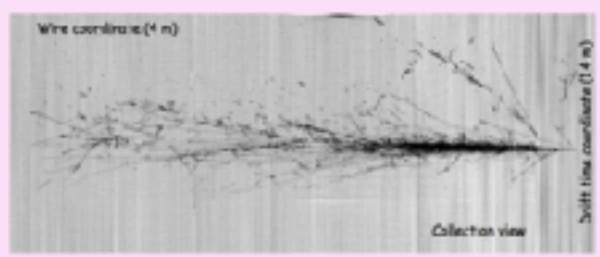




Cheap material, proven at very large scale

Liquid Argon

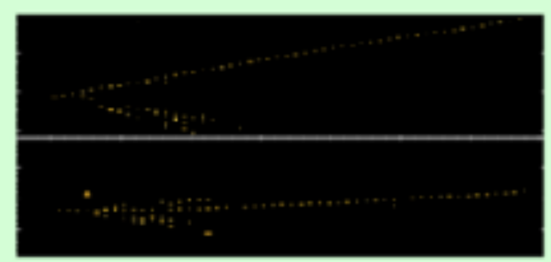




Excellent particle reconstruction

Trackers

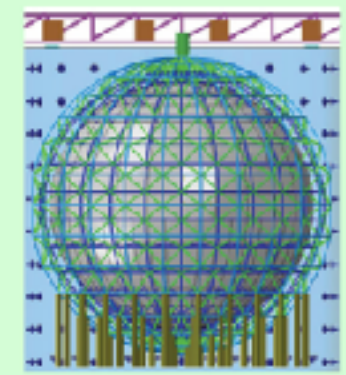
(a diverse category)

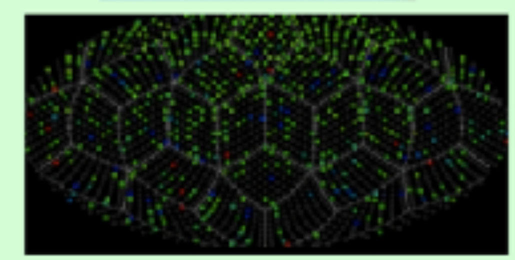


Good particle reconstruction

Liquid scintillator

(and water-based LS)



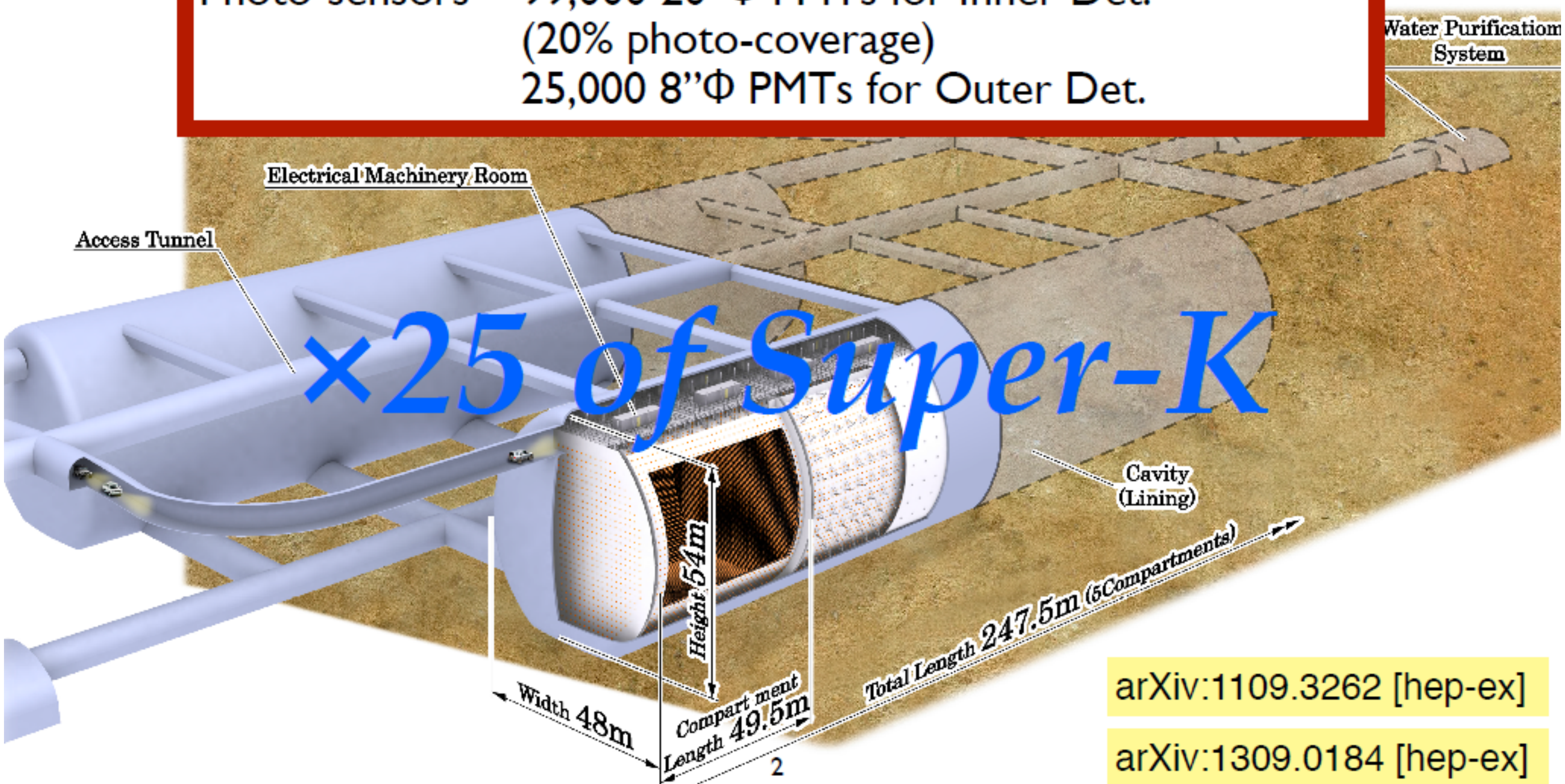


Low threshold, good energy resolution

Water Cherenkov option: HyperK

Hyper-K Overview

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.

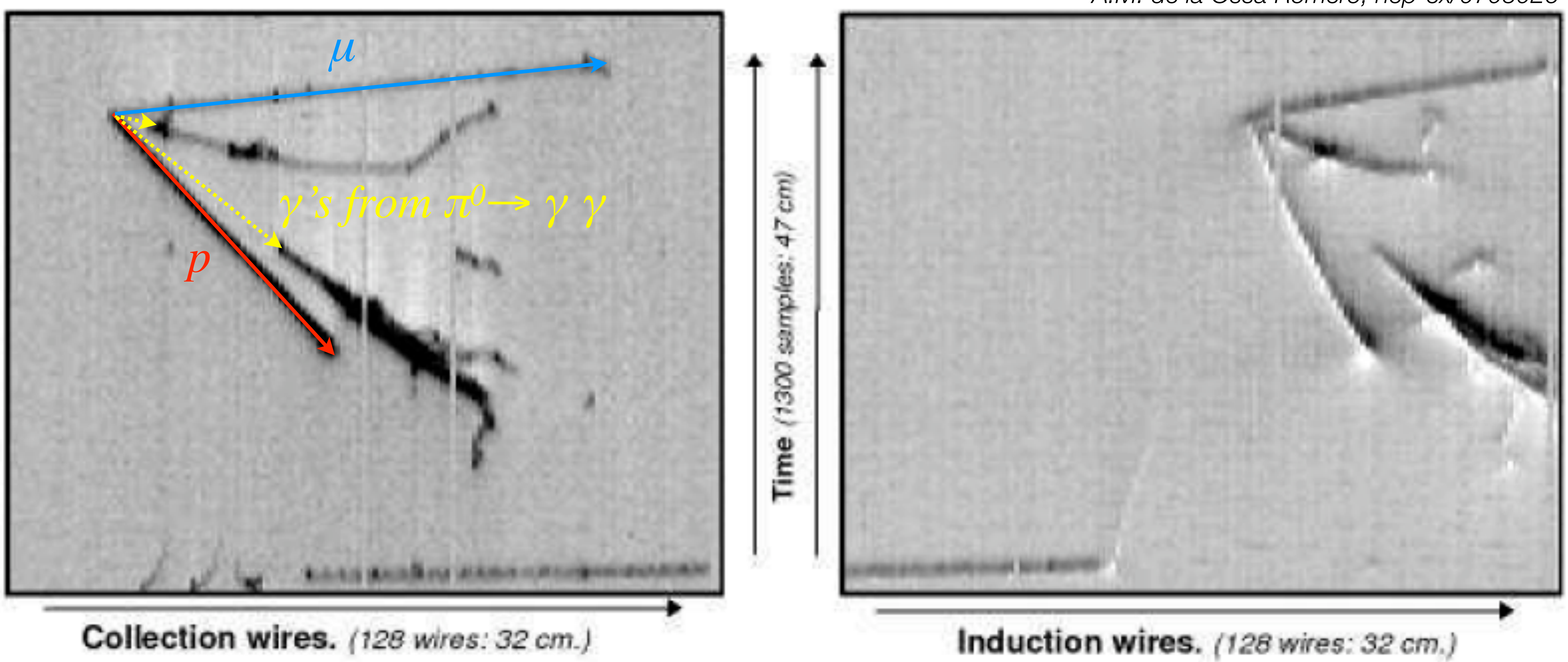


arXiv:1109.3262 [hep-ex]

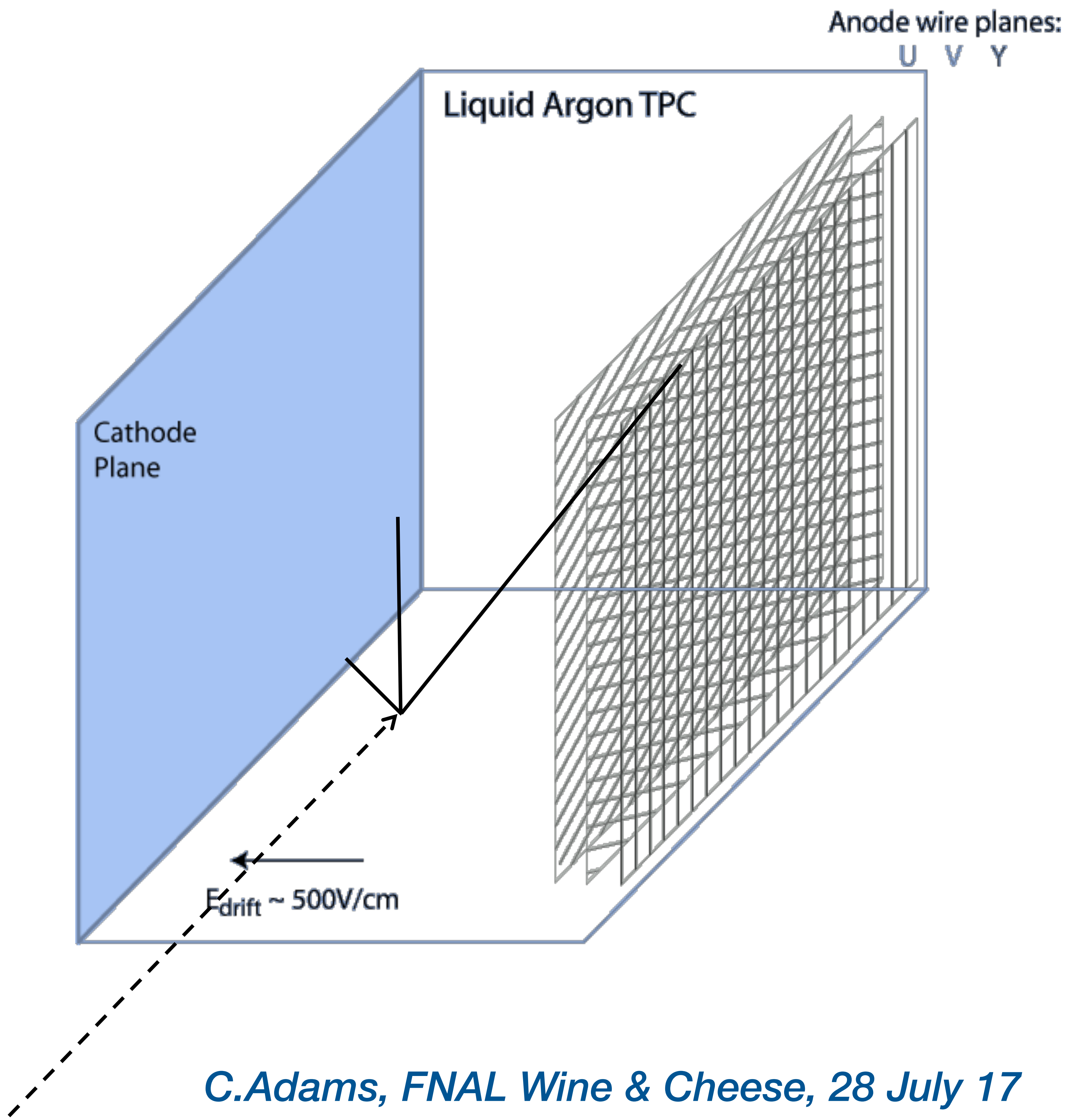
arXiv:1309.0184 [hep-ex]

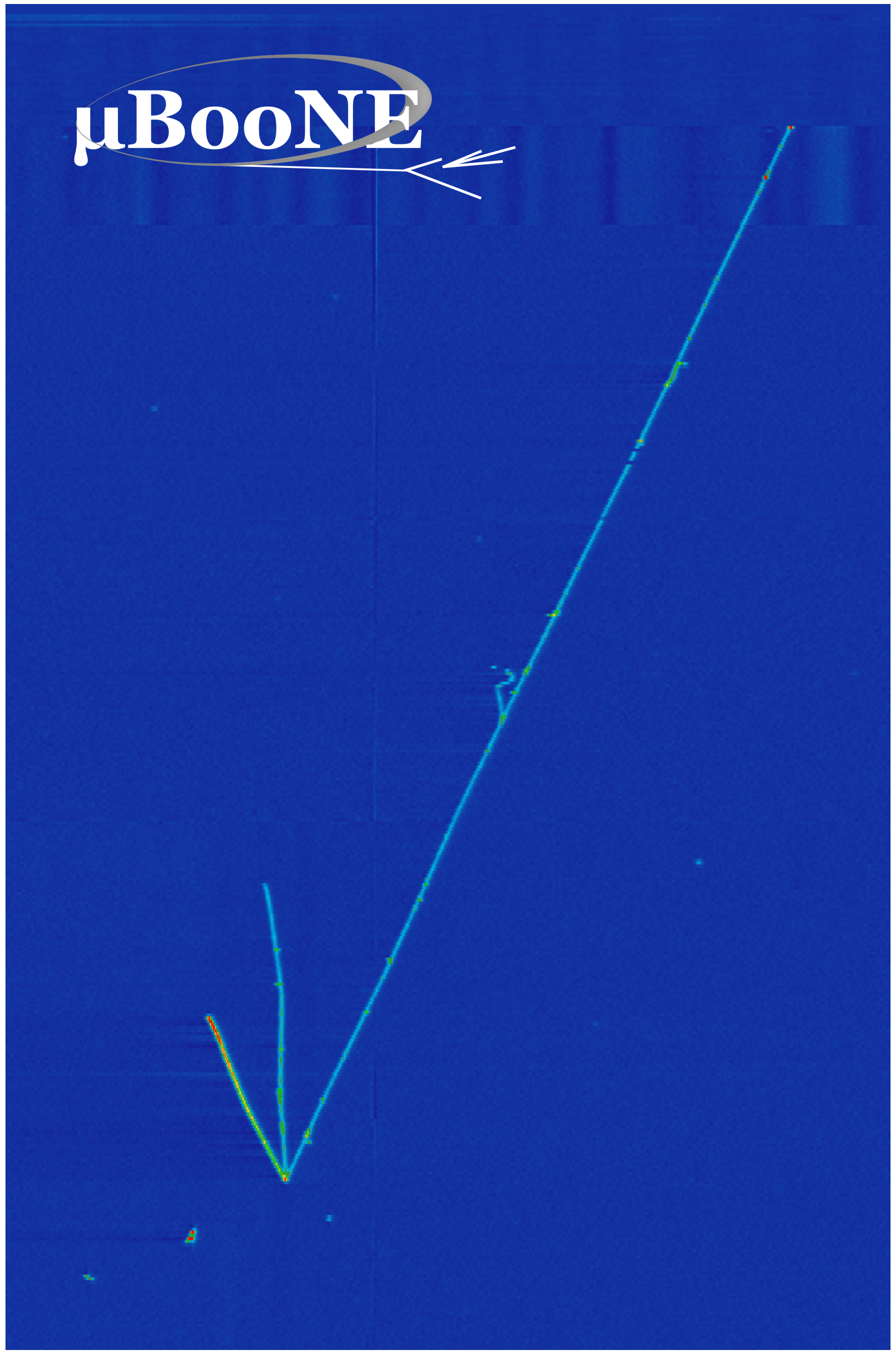
LAr detectors: DUNE, SBN, MicroBooNE…

A.M. de la Ossa Romero, hep-ex/0703026

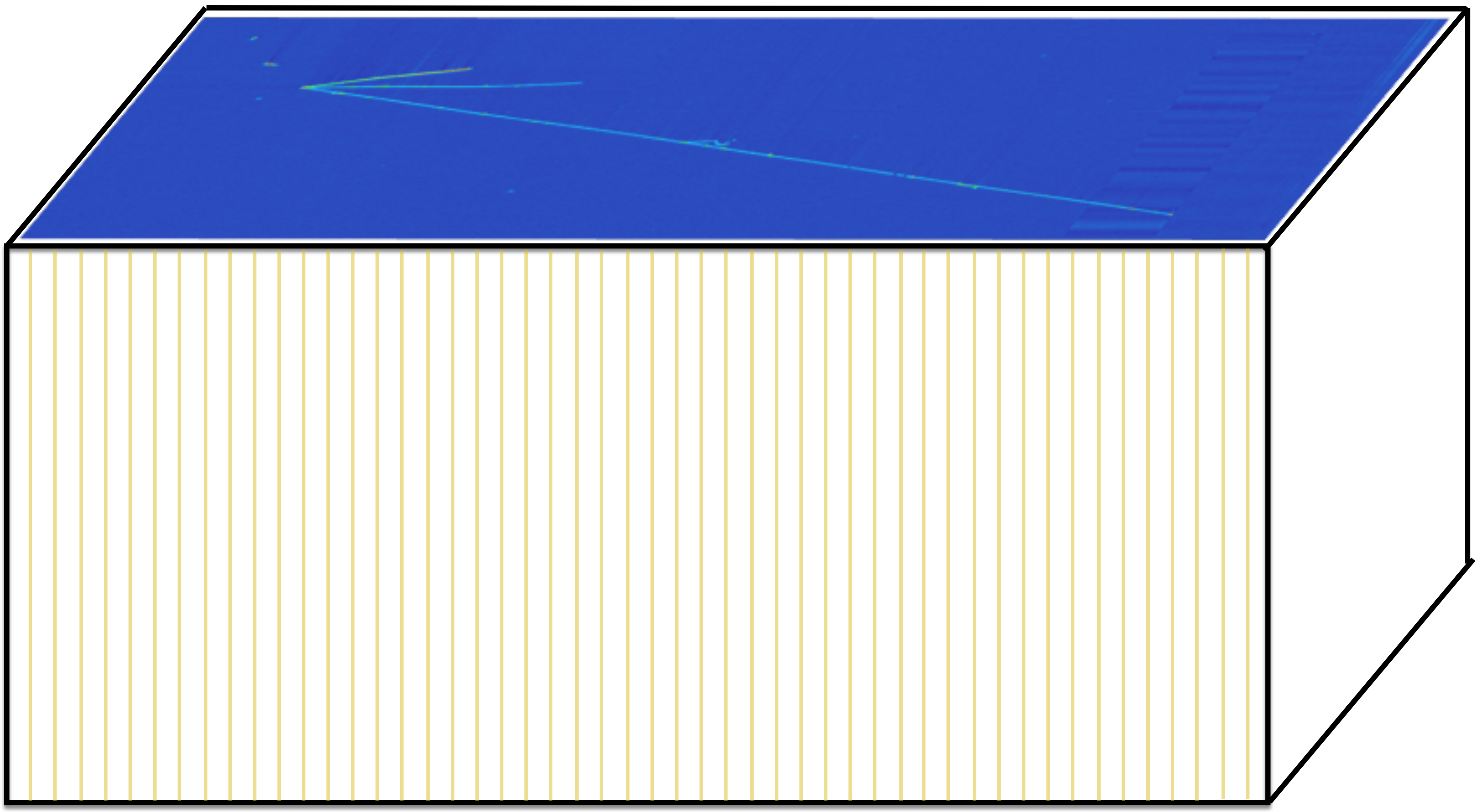


Liquid Argon Time Projection Chambers

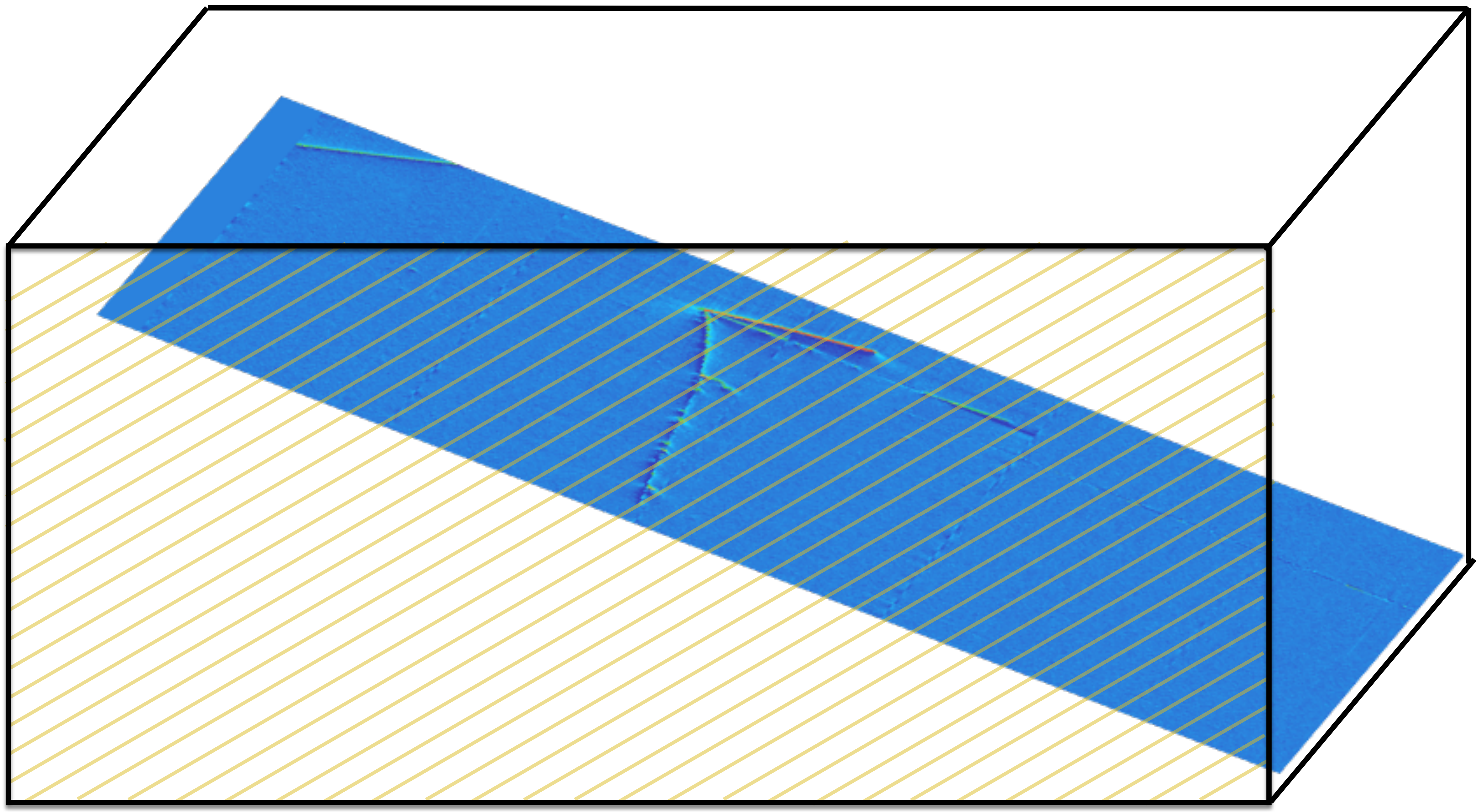




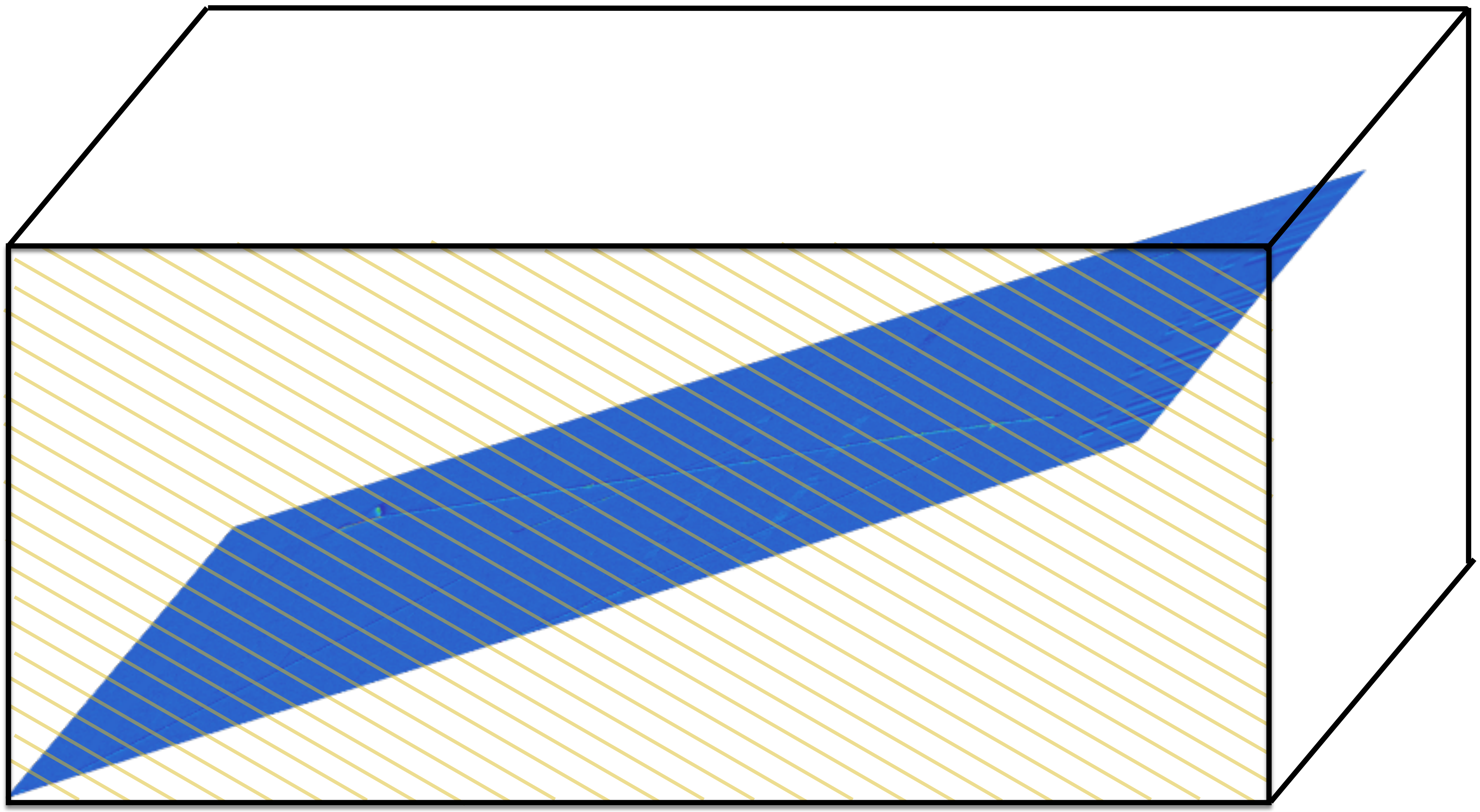
"Projection" Chamber



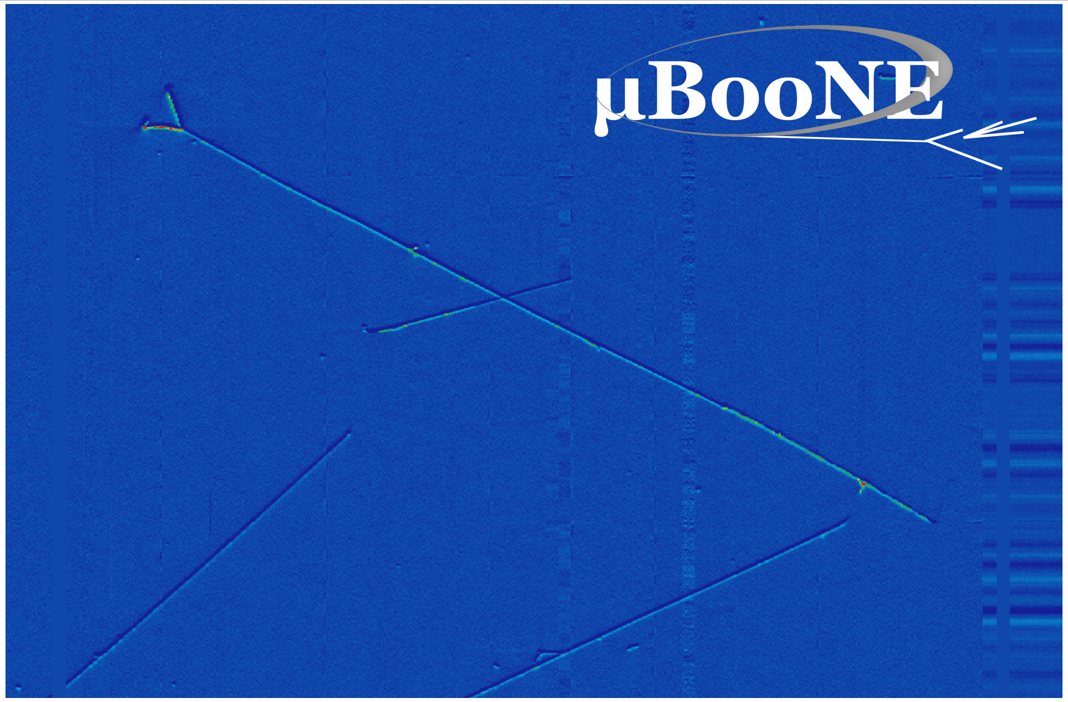
“Projection” Chamber

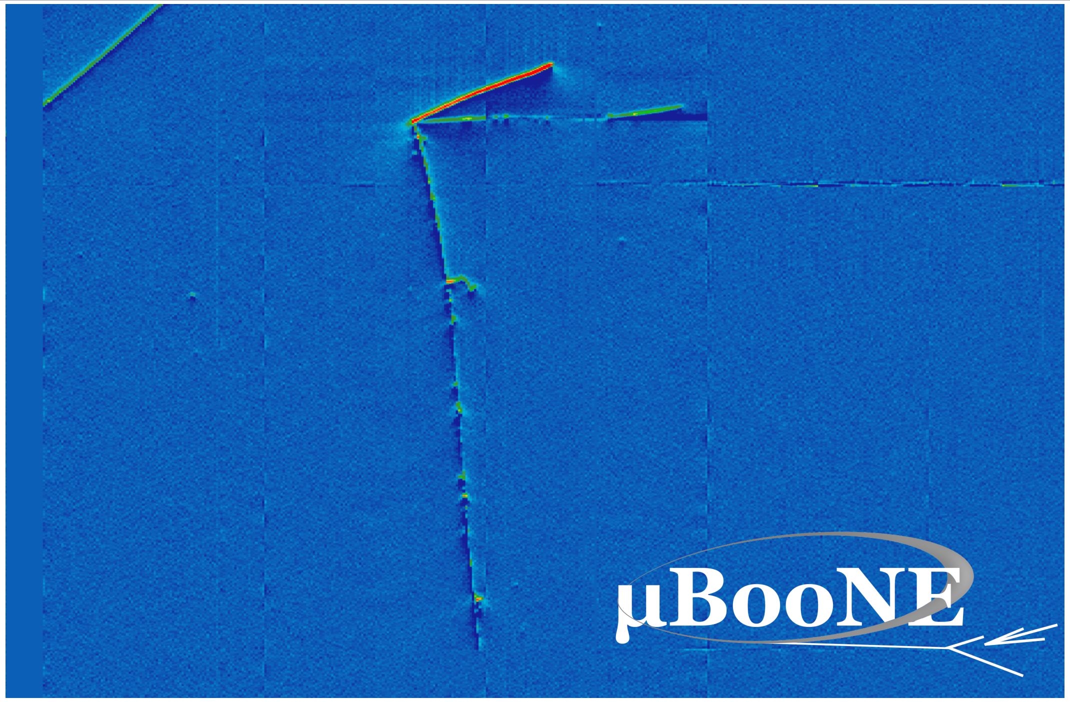


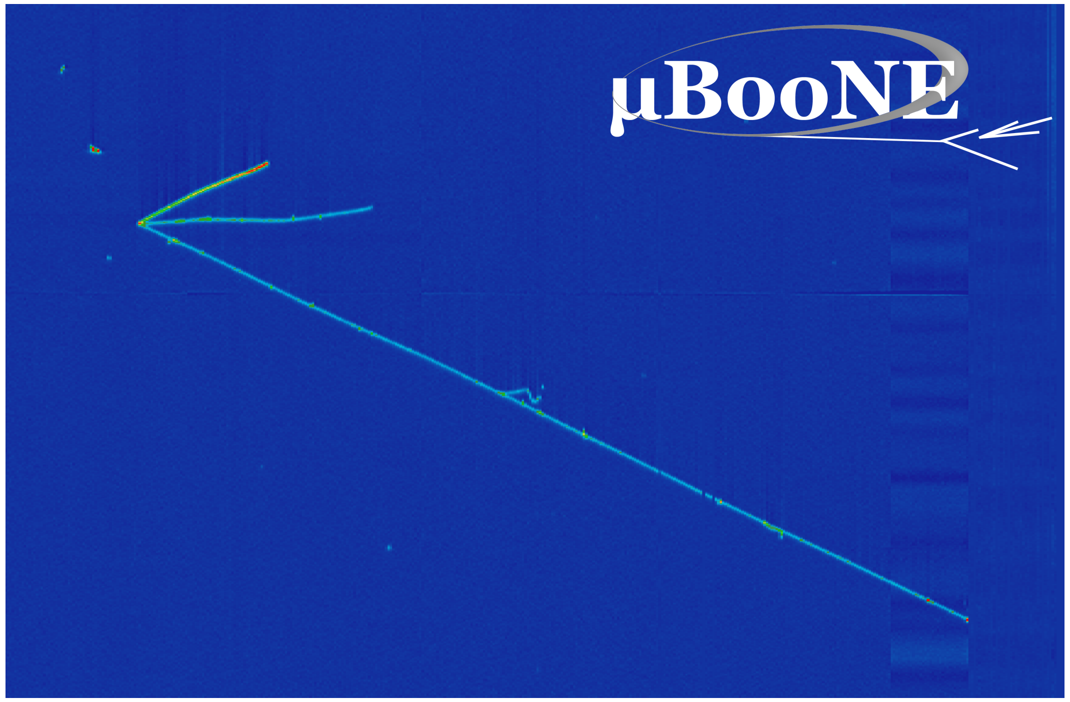
“Projection” Chamber



3 Projections of Same Objects

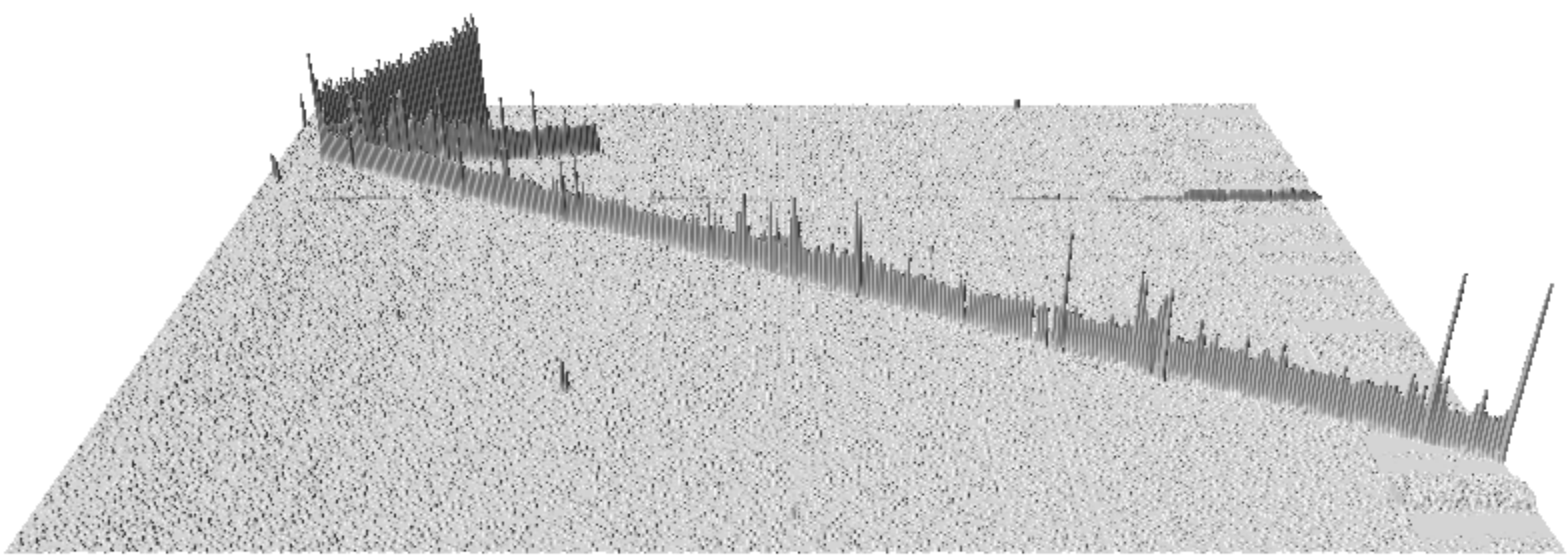




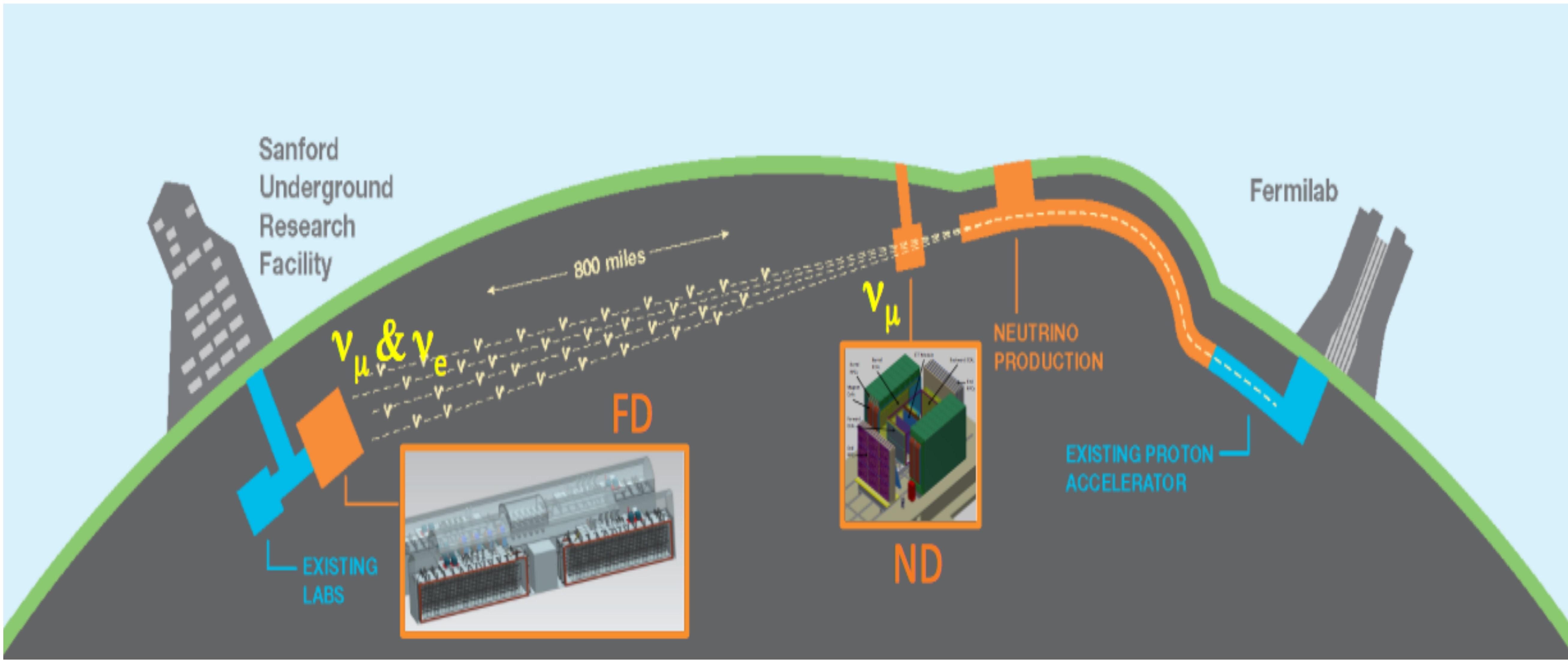


Neutrino Images

Fine grained spatial resolution PLUS charge deposition information

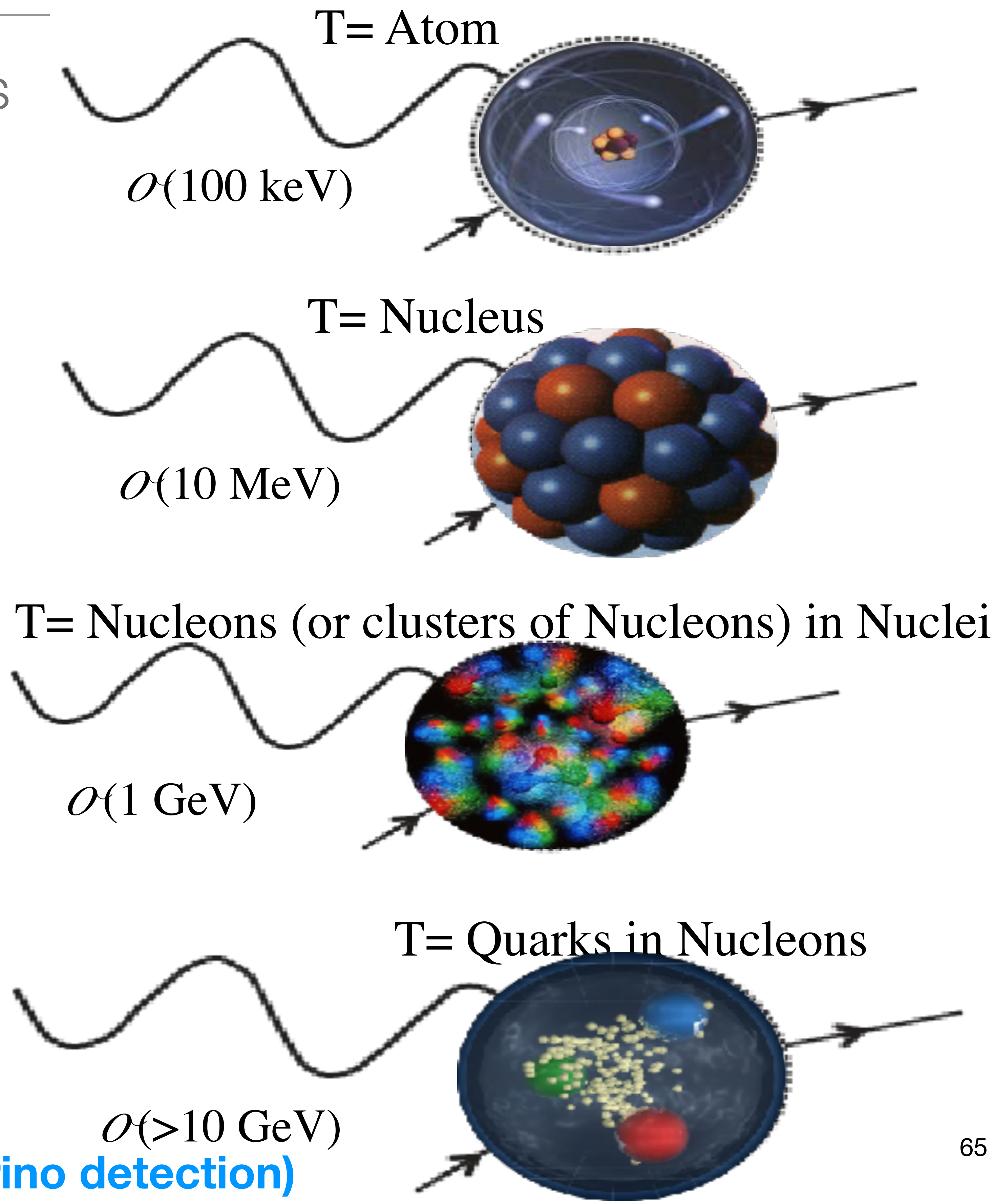


Next step: DUNE



Final word on the challenge of neutrino detections

Very broad range of interactions

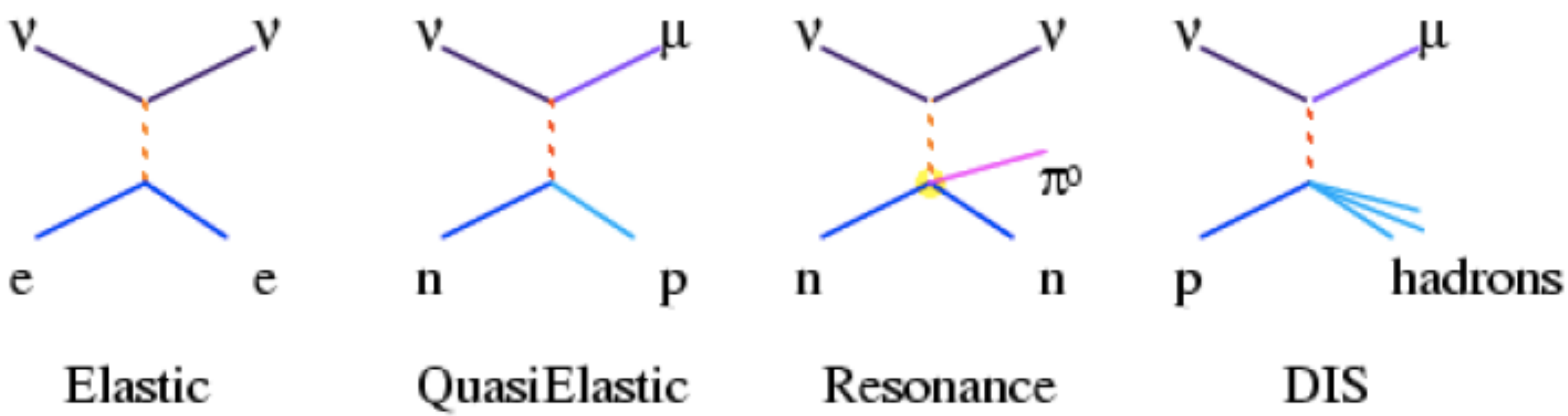


Neutrinos - over such extended range of energies - probe matter from its Atomic structure to the ultimate quark structure.

O. Palamara (2016 Lecture on Neutrino detection)

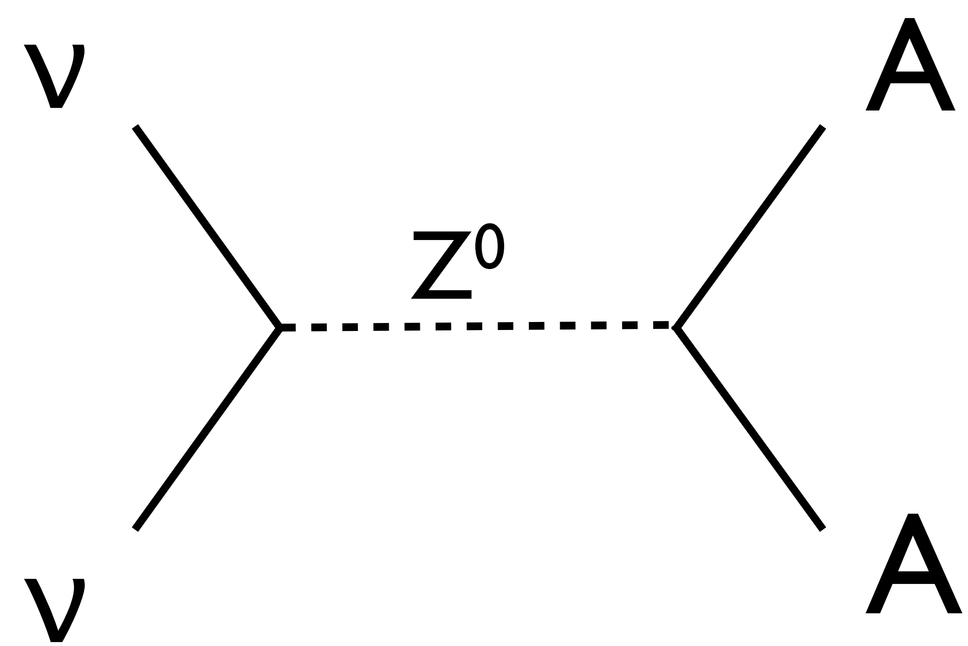
Final word on the challenge of neutrino detections

- Very broad range of interactions



L. Winslow

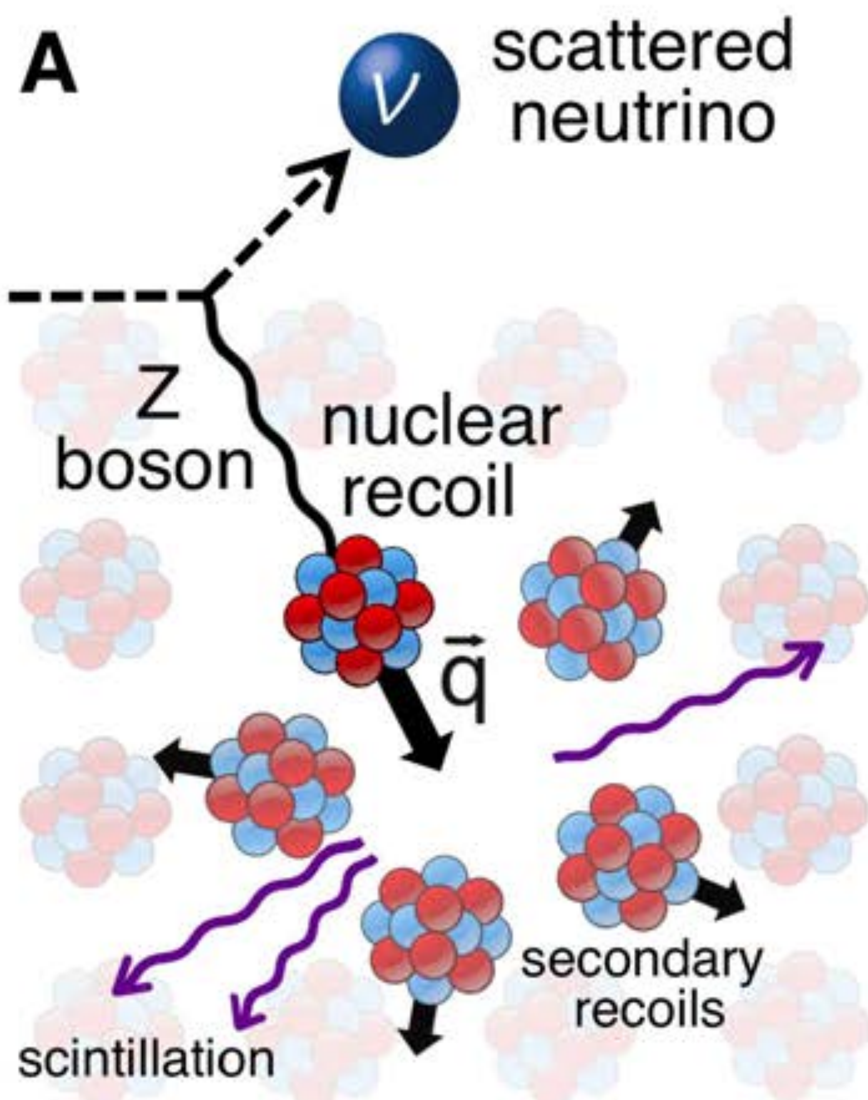
Coherent Scaterring

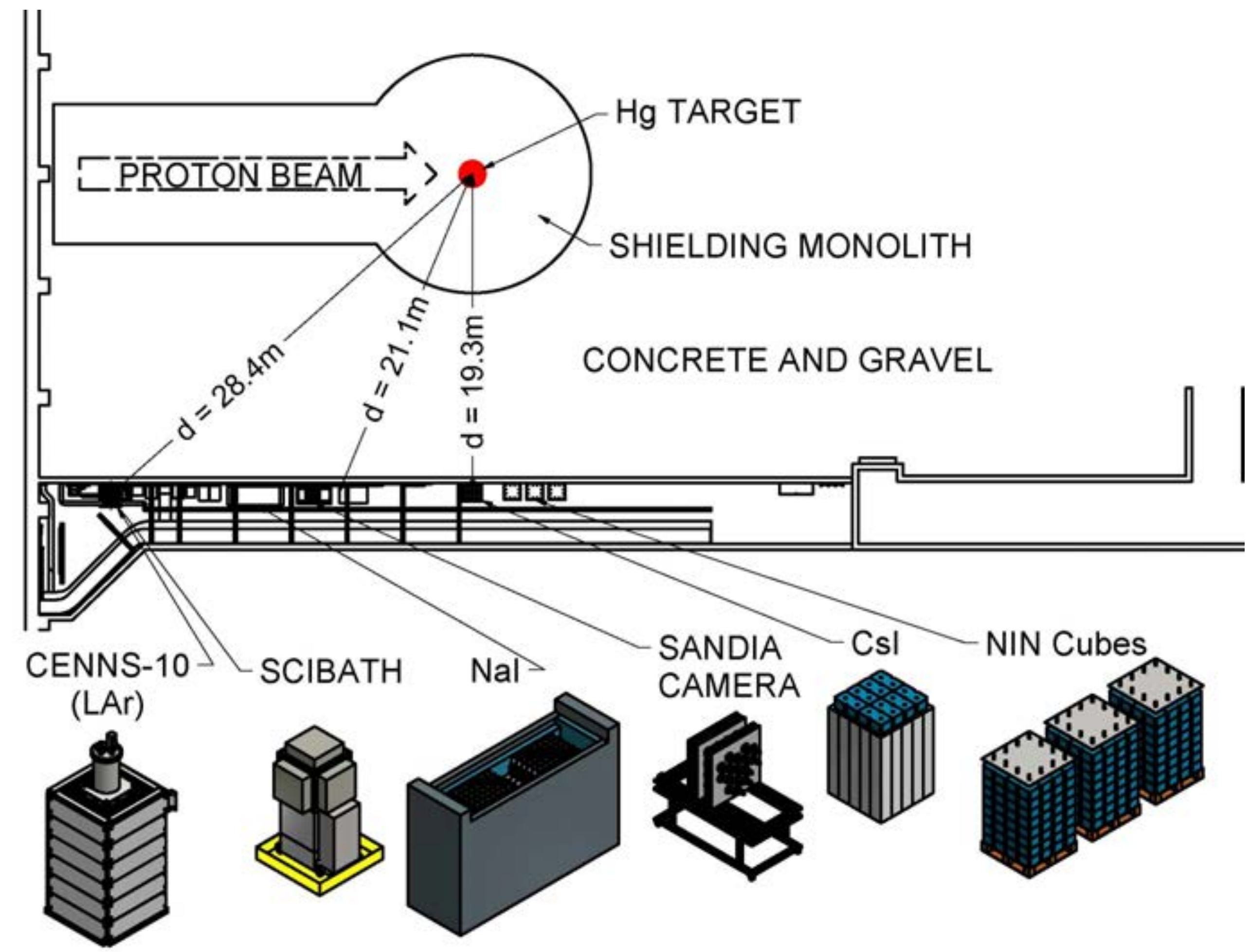


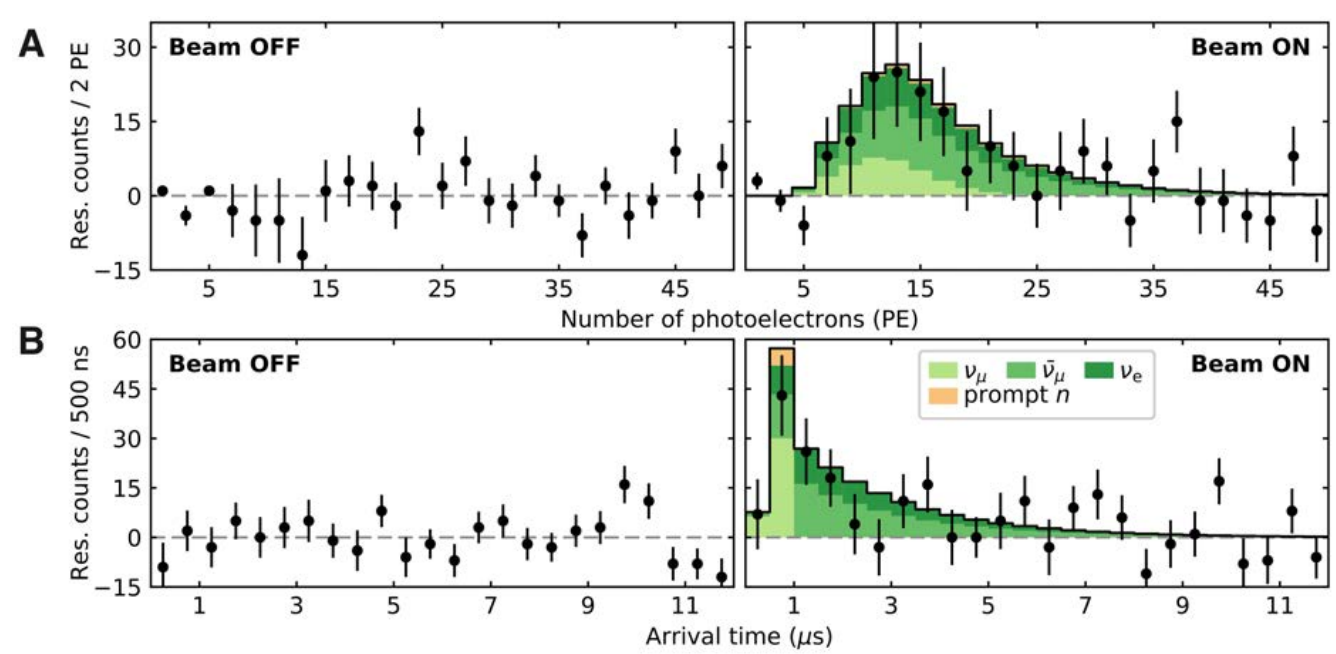
Number to Remember: 50MeV
Above this energy the neutrinos "sees" the constituent neutrons/protons...

L. Winslow

COHERENT detection!







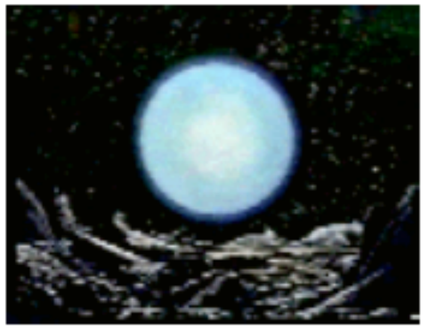
D. Akimov et al., Science (2017)

COHERENT detection!

From K. Scholberg

Why try to measure this?

- It's never been done!



- Important in supernova processes
- Important for supernova ν detection

- Deviations from expected x-scn may indicate non-SM processes

???

- Possibly even applications..

e.g. Barbeau et al., IEEE Trans. Nucl. Sci. 50: 1285 (2003)
C. Hagmann & A. Bernstein, IEEE Trans. Nucl. Sci 51:2151 (2004)

Conclusion

- Neutrino detectors need to be huge!
- No detection techniques can be applied to all energies
- Neutrinos have a lot to teach us still and we should continue to explore all the possibilities
- It’s not obvious where the great next discoveries will be
- Let’s keep looking and inventing new ways!

A brief history of LAr technology

- 1968: L.W. Alvarez first proposes the use of Liquid Noble Gases for particle detectors

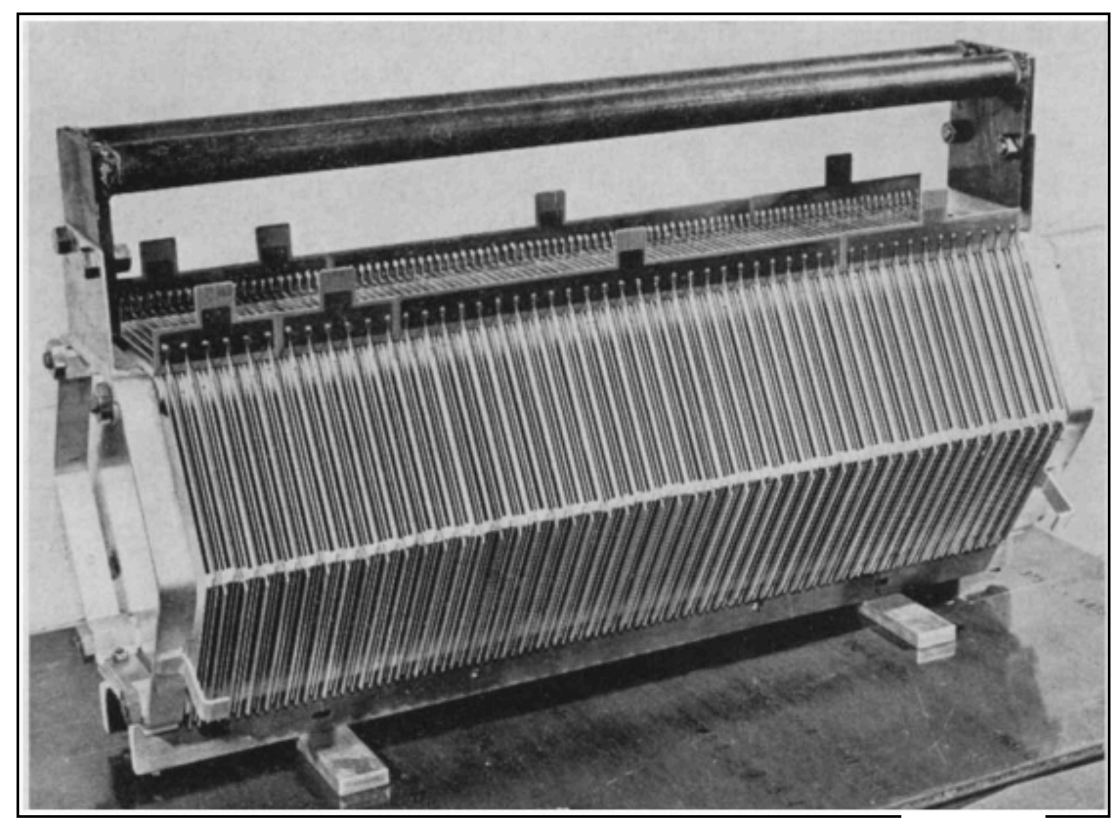
- 1974: W. Willis and V. Radeka propose the use of LAr ionization chambers

  - LAr one of best materials to answer traditional calorimeters limitations

i) it is dense (1.4 g/cm^3);
ii) it does not attach electrons;
iii) it has a high electron mobility ($\sim$5 mm/μs at 1 kV/mm);
iv) the cost is low (\$0.14→0.50/kg, depending on source and quantity);
v) it is inert, in contrast to flammable scintillators;
vi) it is easy to obtain in a pure form and easy to purify;
vii) many electronegative impurities are frozen out in liquid argon.

The disadvantage is that the container must be insulated for liquid-argon temperature (86 K).

Willis & Radeka, NIM 120 (1974)



A brief history…

- In the 70's, neutrino detectors fall into 2 categories:
    - ➢ Small sensitive mass and high resolution bubble chambers
    - ➢ More massive detectors (only few event features are detected)
- Need for novel neutrino detection technology that combines larger mass with high resolution event

→ Carlo Rubbia proposes LArTPC (1977)

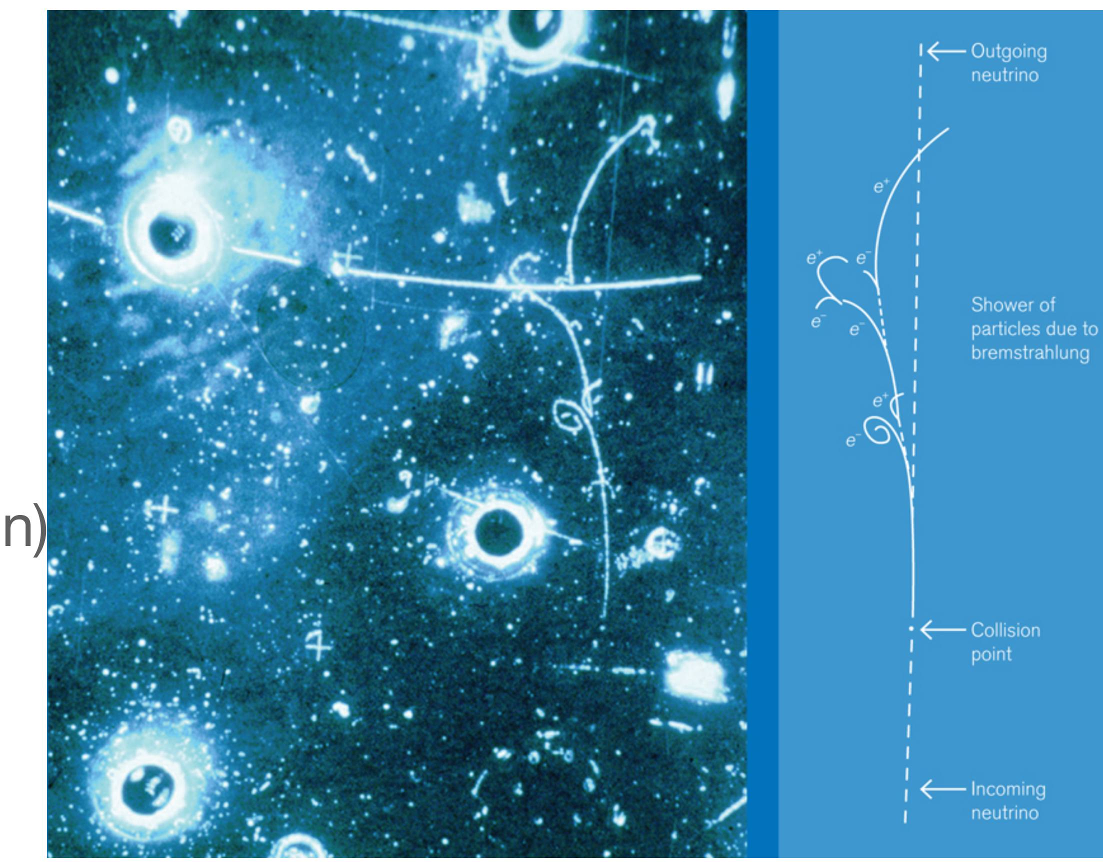
Traditional neutrino detection technologies

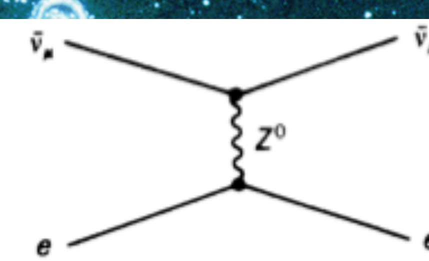
Bubble Chambers: e.g. Gargamelle

- Long era of BC in particle physics (1952 to 1970's)
- Culminated with the discovery of Neutral Current interaction (1973)

Limitations:

- ➢ Low density
- ➢ Slow response time (~1sec. for recompression)
- ➢ Not scalable to very large scale





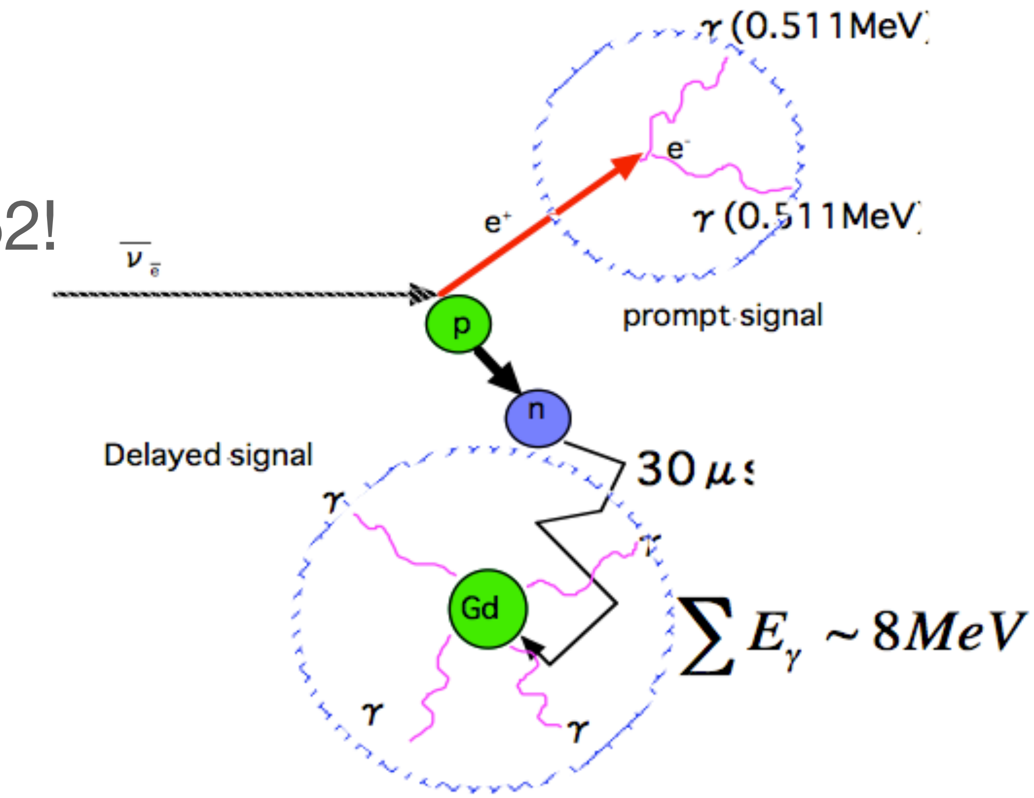
$$\bar{\nu}_\mu e \longrightarrow \bar{\nu}_\mu e$$

Traditional neutrino detection technologies

Doped Liquid Scintillators:

- Used in the neutrino discovery experiment in 1952!

- Can reach lower detection energies (opens the scientific reach)

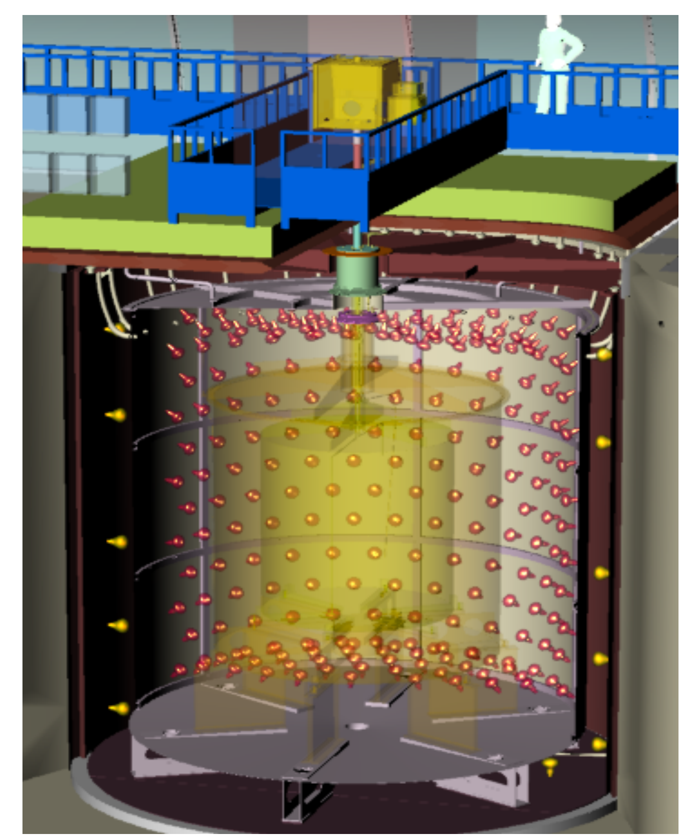


Limitations:

➢ Scalability limited due to light attenuation length

➢ Need low radiation material container and radiation buffers

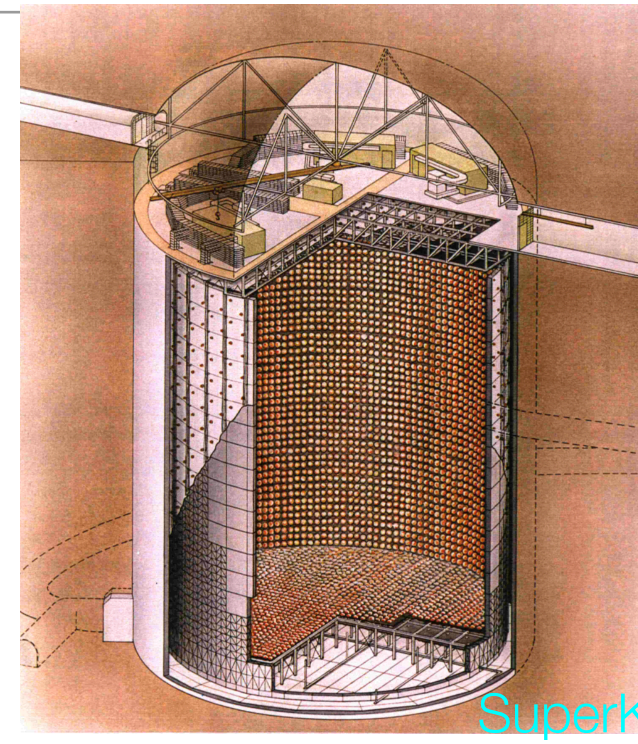
➢ Background limited since only coincidence signals are detected (random coincidences, fast neutrons, ^{8}He/^{9}Li, …



Traditional neutrino detection technologies

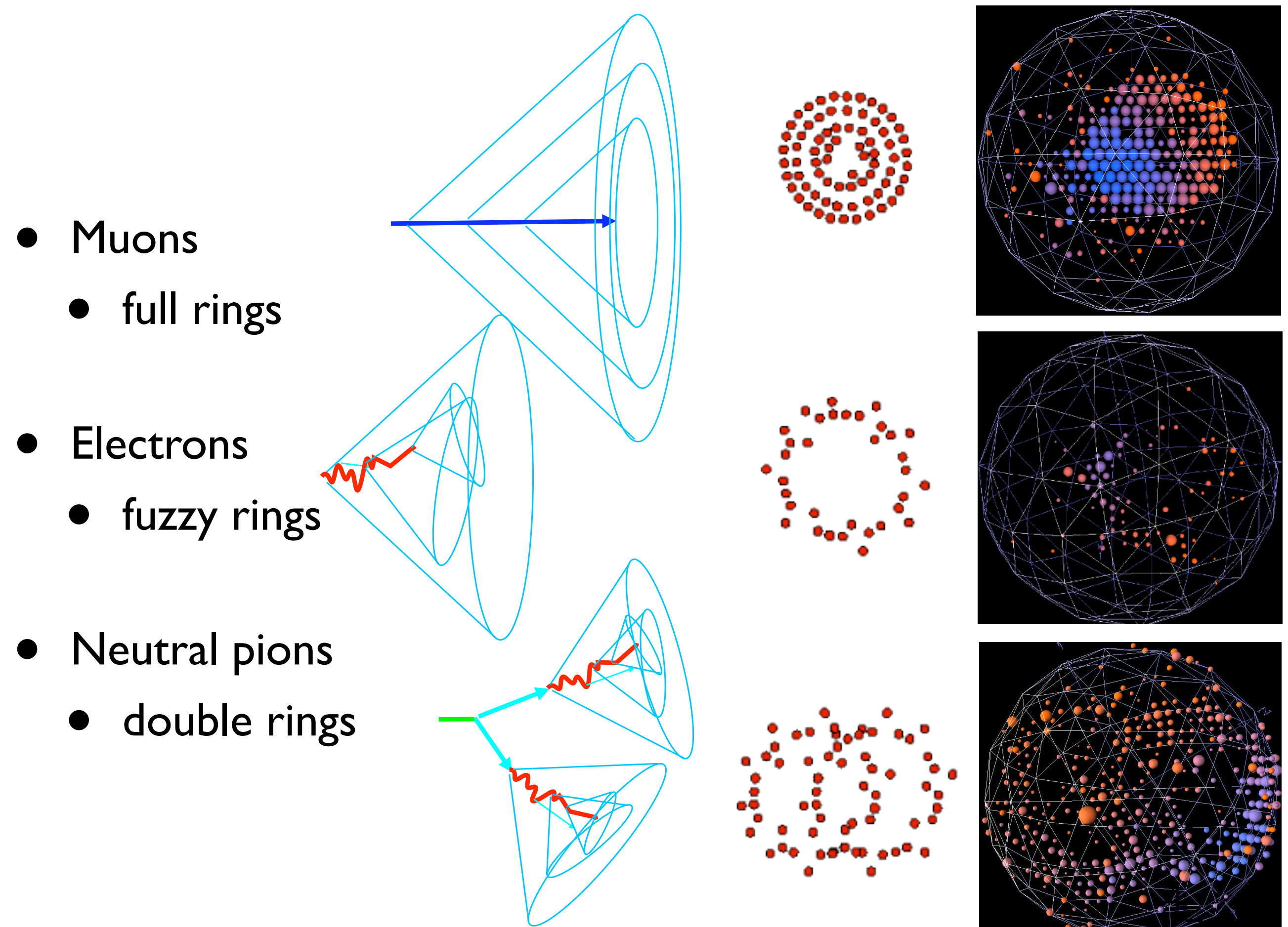
Water Cherenkov:

- Discovery of neutrino oscillations!
- Allows very large volumes (SuperK = 50ktons)
- Technology very well understood

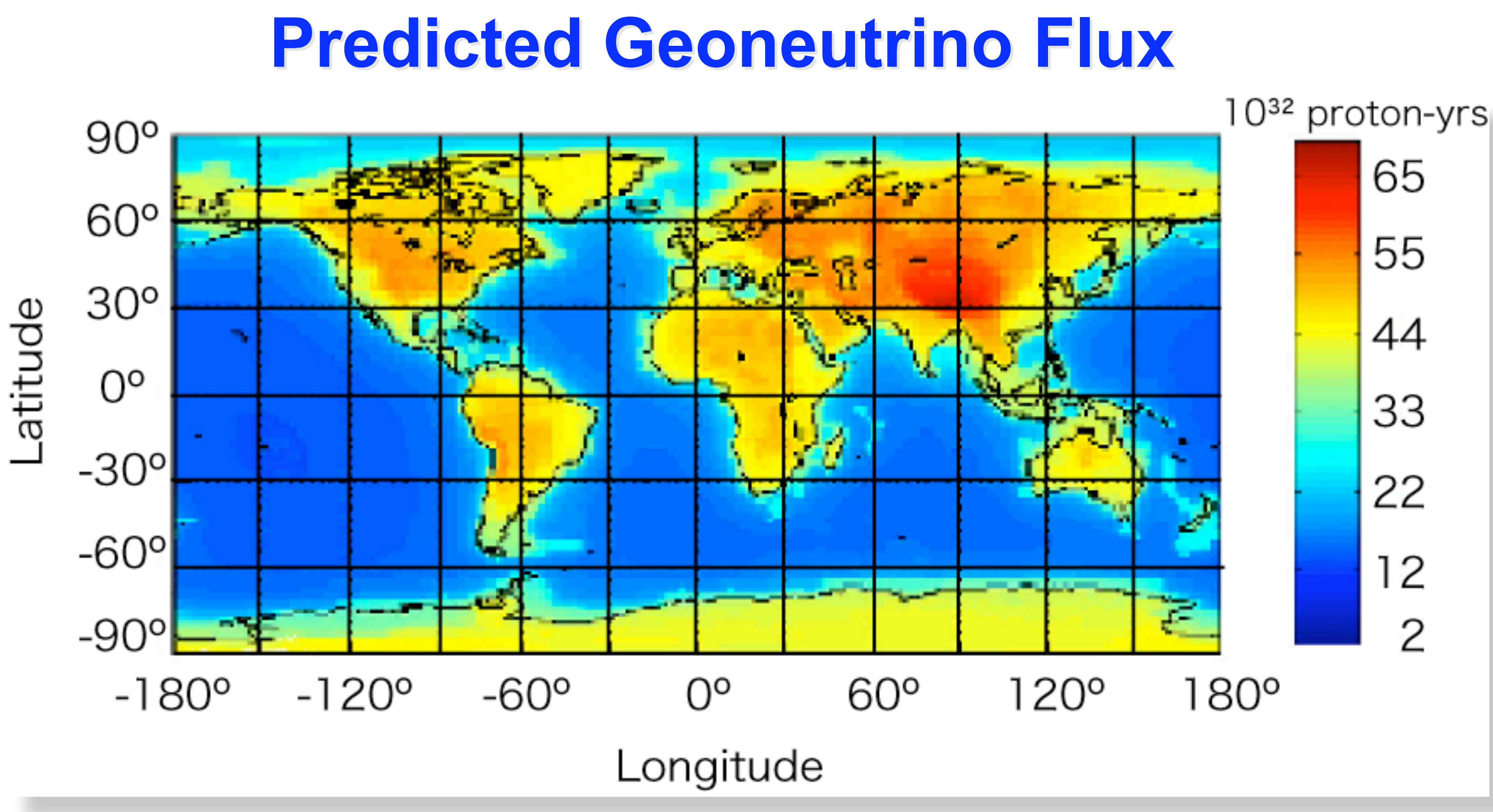


Limitations:

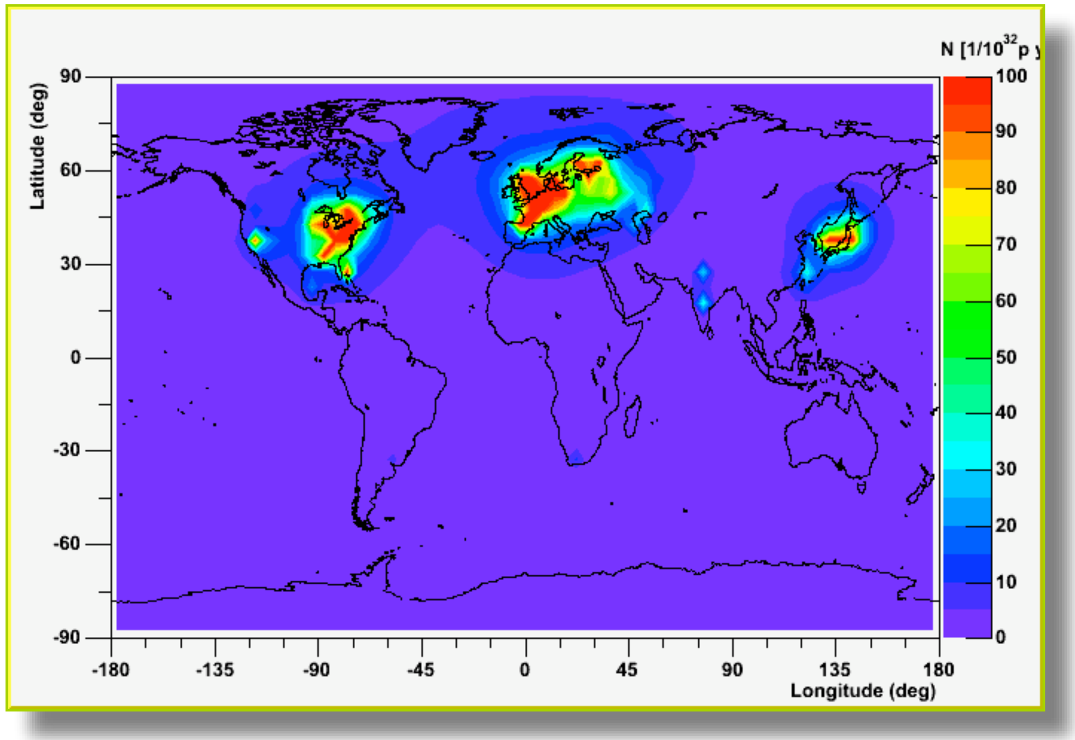
- ➢ Background limited due to e/γ identical signature
- ➢ Particles below Cherenkov threshold not detected
- ➢ Big! Need big cavern ($$$)



Geoneutrinos



Reactor Flux - **irreducible background**



Geoneutrinos

Geoneutrinos: electron antineutrinos
from the decays of long lived radioactive isotopes
naturally present in the Earth (^{238}U and ^{232}Th chains and ^{40}K)

^{238}U (99.2739% of natural U)	→ $^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + **51.7 MeV**
^{232}Th	→ $^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + **42.8 MeV**
^{235}U (0.7205% of natural U)	→ $^{207}Pb + 7\,\alpha + 4\,e^- +$ 4 anti-neutrinos + **46.4 MeV**
^{40}K (0.012% of natural K)	→ $^{40}Ca + e^- +$ 1 anti-neutrino + **1.32 MeV** (89.3 %)
$^{40}K + e^-$	→ $^{40}Ar +$ 1 neutrino + **1.505 MeV** (10.7 %)

the only direct probe of the deep Earth

released heat and anti-neutrinos flux in a well fixed ratio

measure geoneutrino flux = (in principle) = get radiogenic heat

in practice (as always) more complicated…..

Earth shines in antineutrinos: flux ~ 10^6 cm^{-2} s^{-1}
leaving freely and instantaneously the Earth interior
(to compare: solar neutrino (NOT antineutrino!) flux ~ 10^{10} cm^{-2} s^{-1})

Geoneutrinos

Mantle is depleted in some elements (e.g., Th & U) that are enriched in the continents.

-- models of mantle convection and element distribution